IN WINO VERITAS?

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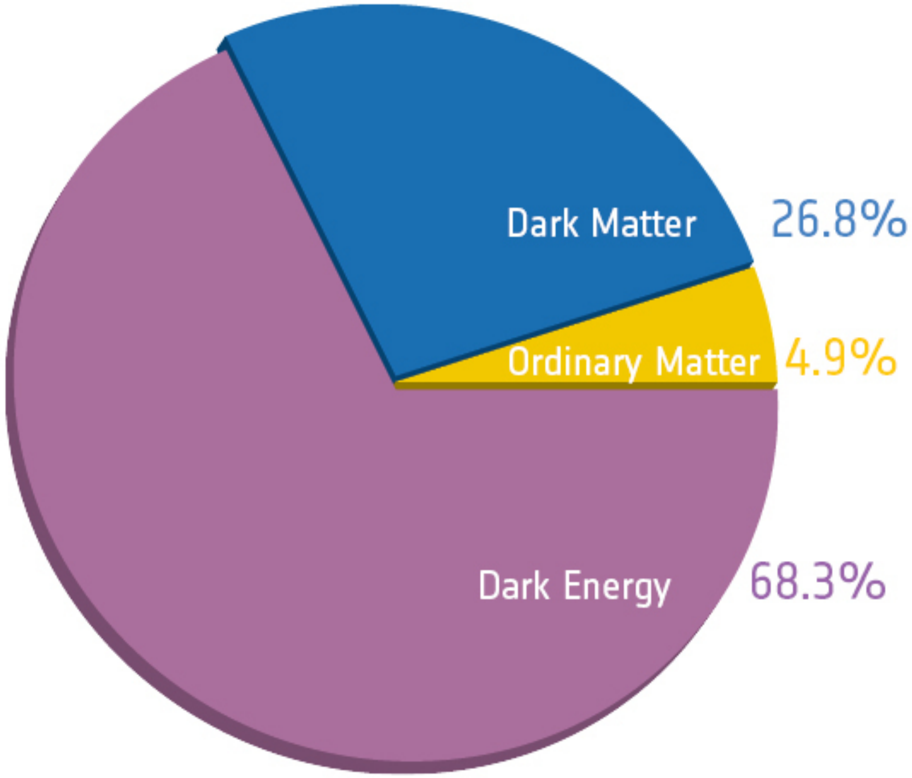
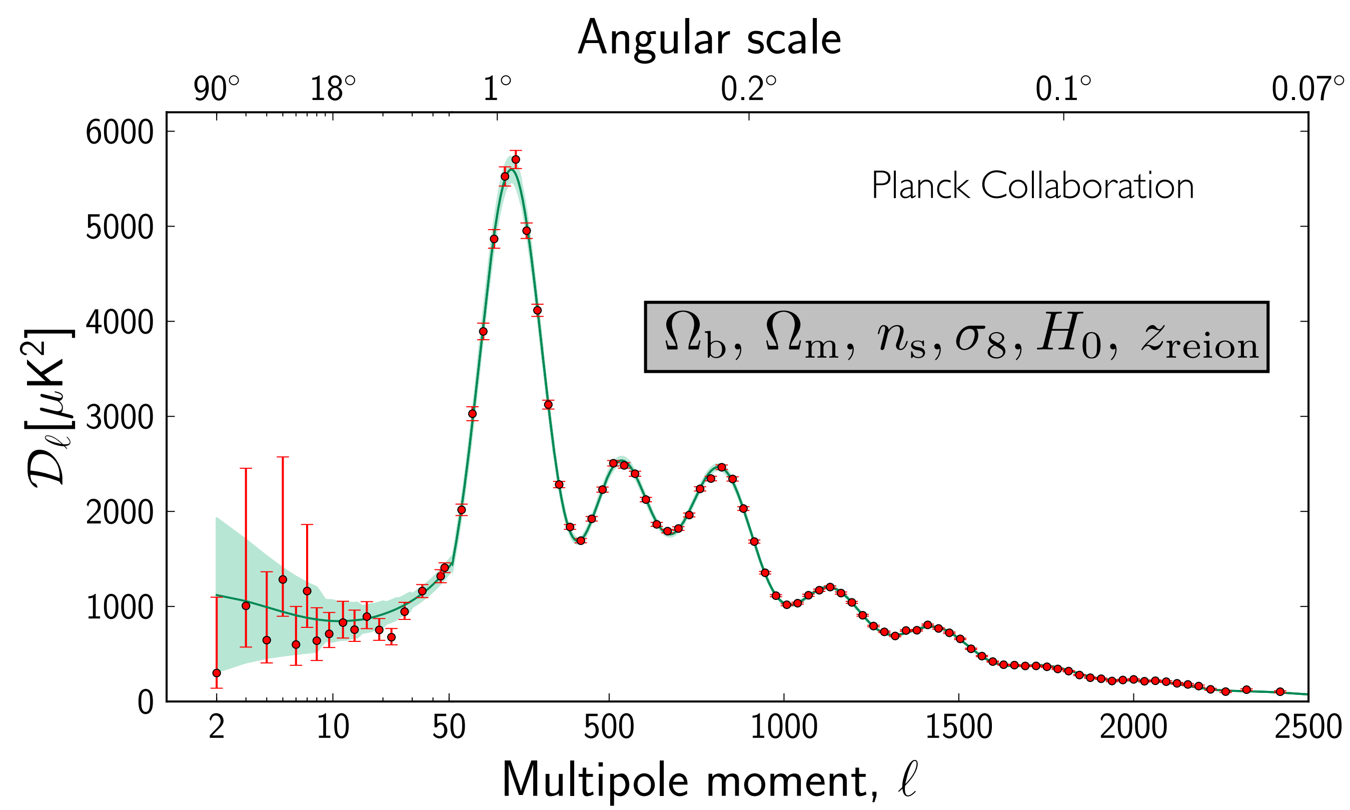
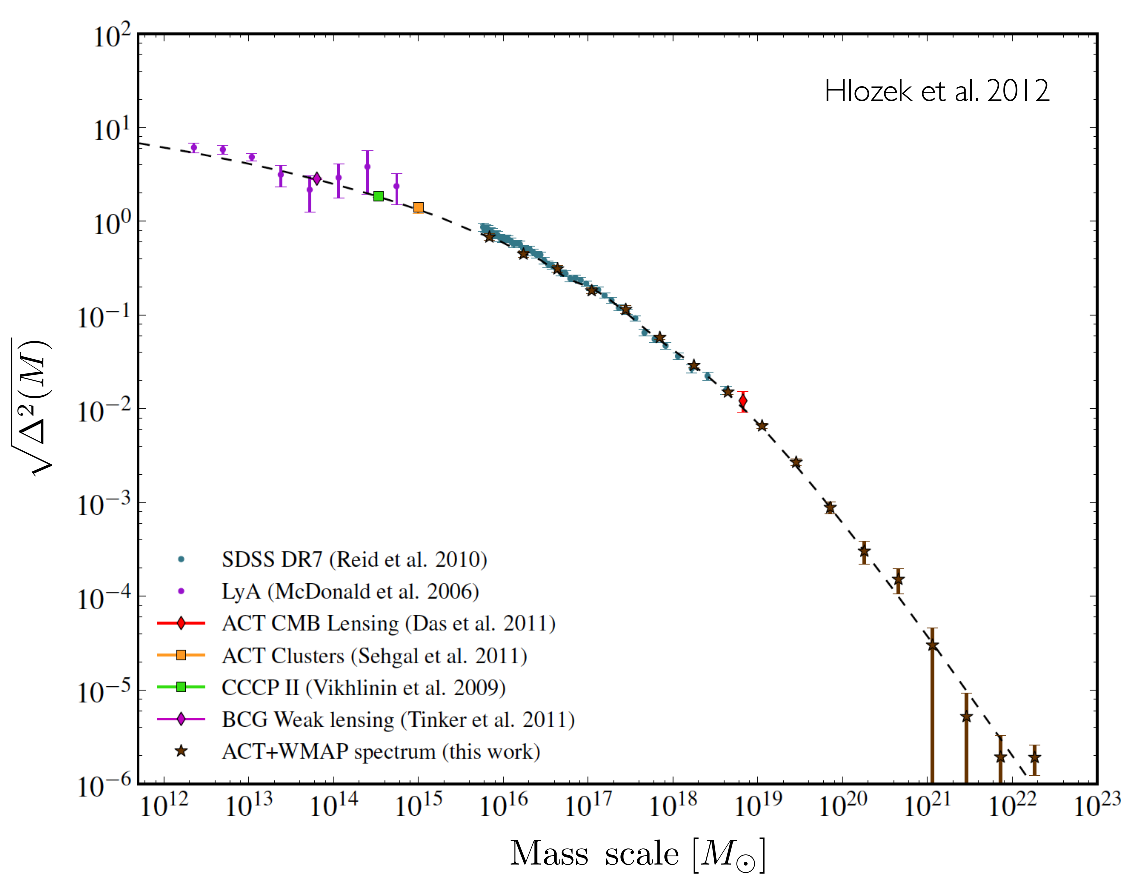
Harvard University
at Fermilab, July 23, 2014

based on: 1307.4400 by JiJi Fan and MR

WHAT IS DARK MATTER?







It's most of the mass in the universe, gives precise fits to structure formation and the CMB.... But what *is* it?

PARTICLE DARK MATTER

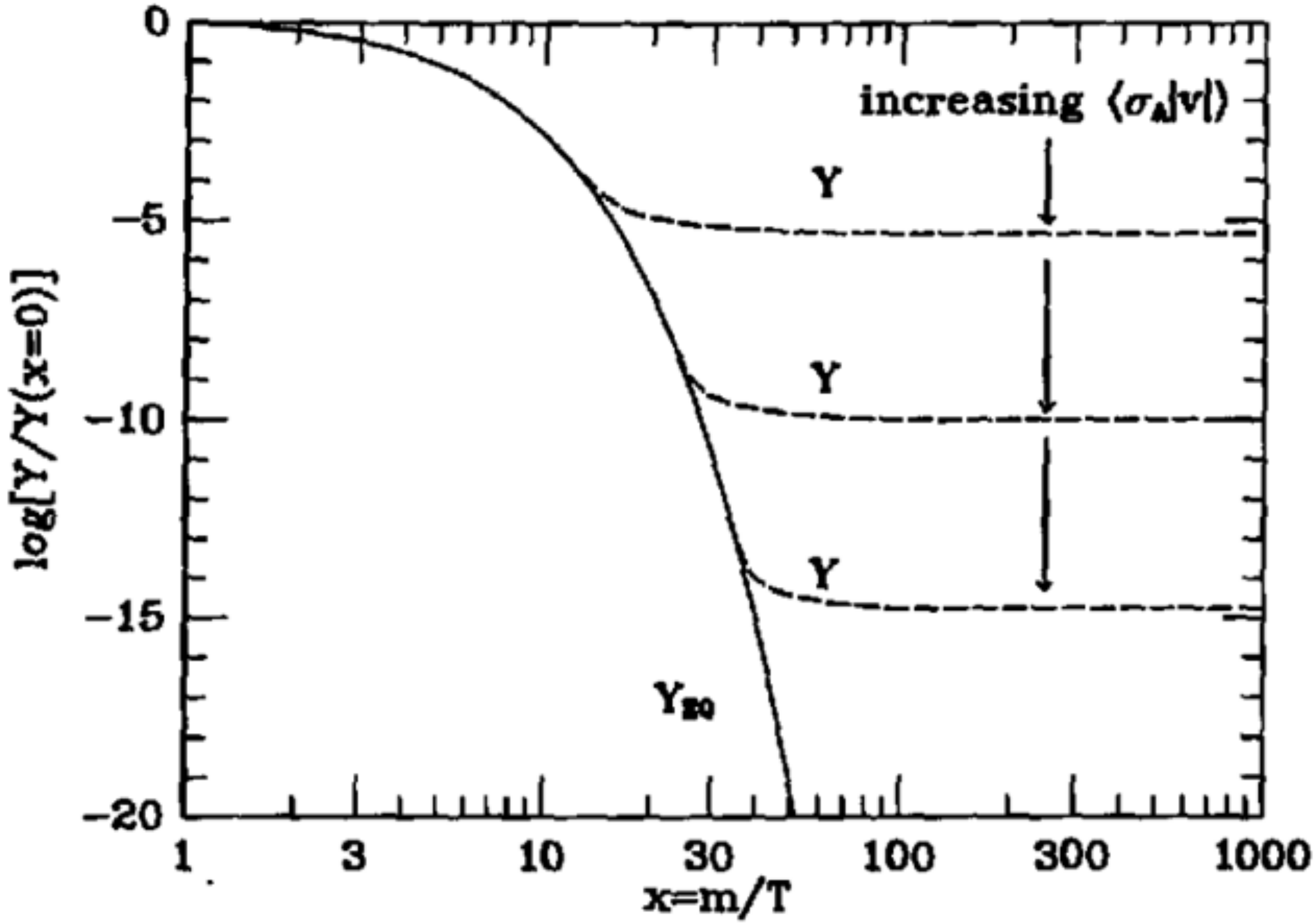
Dark matter candidates arising from models of particle physics beyond the Standard Model are a dime a dozen.

It's very easy to find particles that are stable, either because they are the lightest state carrying some charge, or just by accident.

Today I'll focus on MSSM neutralinos, a well-motivated option that is coming under significant strain due to data.

THERMAL FREEZEOUT

Dark matter in equilibrium with the SM tracks thermal abundance until the Hubble expansion is faster than the interactions



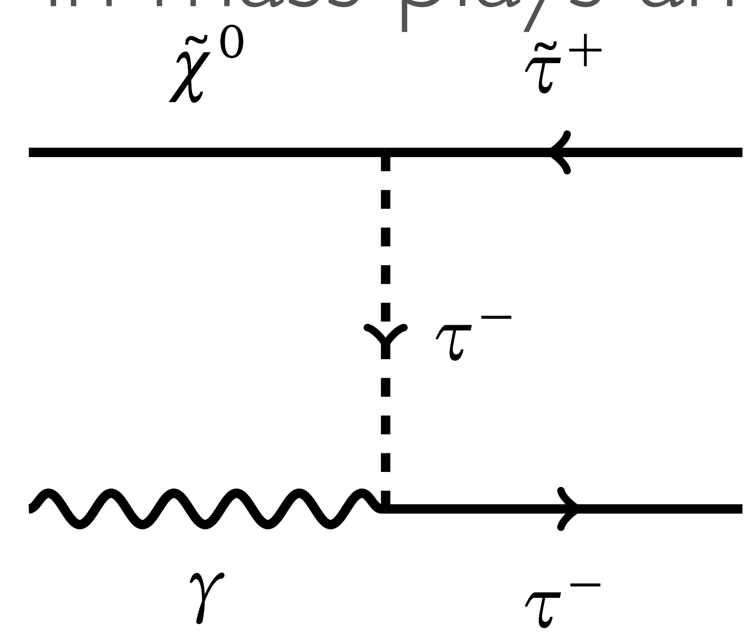
$$\Omega_{\rm DM} h^2 \approx 0.1 \left(\frac{3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \right).$$

LOOPHOLES

Dark matter can be a **thermal relic** even if its present-day annihilation cross section is not $3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$.

There are a number of loopholes that allow the annihilation rate *today* to be different from what established the DM abundance in the early universe.

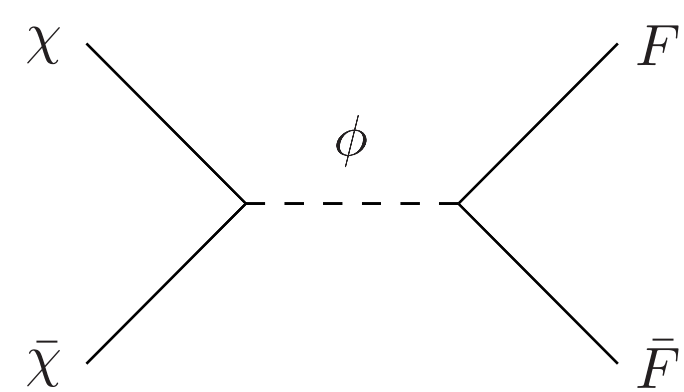
1. **Coannihilation**: another particle nearby in mass plays an important role in equilibrating the DM.



Result: **lower-than-expected** cross section in the current universe. Griest, Seckel '91

LOOPHOLES

2. **Annihilation to slightly heavier states**: very similar to coannihilation.



Both require new masses within about 10% of DM mass. Accident, or symmetries.

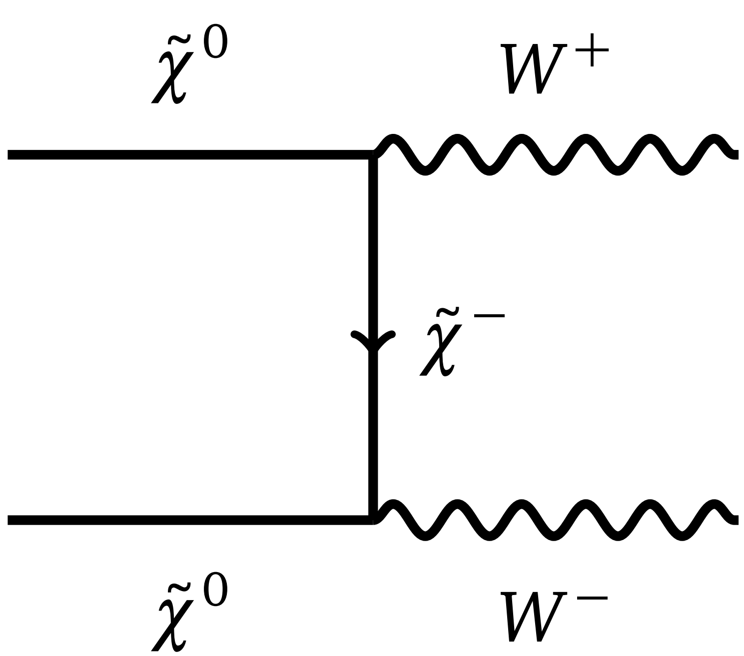
Griest, Seckel '91; Tulin, Yu, Zurek 1208.0009

3. **p-wave annihilation in the early universe**. Suppressed now because DM is non-relativistic ($v \sim 10^{-3}$)

4. **Sommerfeld enhancement** today: cross section in the early universe was lower because velocities were higher

MSSM DARK MATTER

Neutralinos: superpartners of photon, Z, and Higgs.



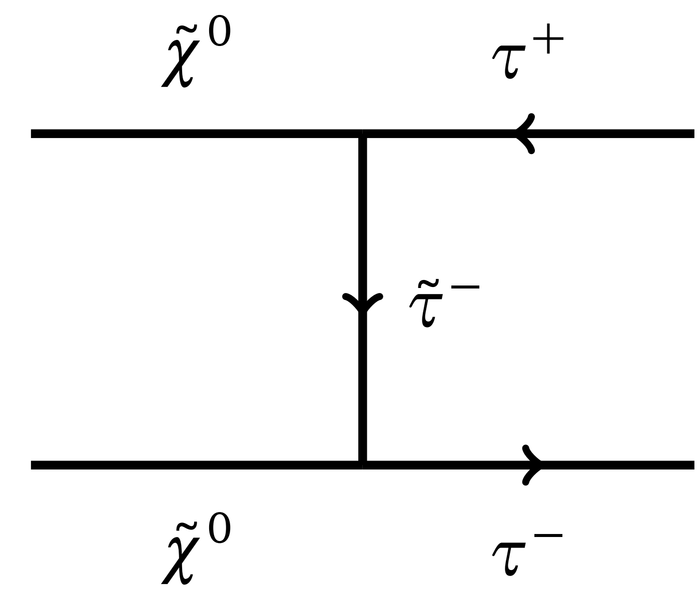
Wino and higgsino: in SU(2) multiplets; can annihilate a lot.

Thermal relic abundance is underpopulated unless they're heavy (about 1 TeV for higgsinos or 3 TeV for winos), e.g.:

$$\langle \sigma v(\chi\chi \to W^+W^-)\rangle \approx 3 \times 10^{-24}\frac{\text{cm}^3}{\text{s}} \text{ for } m_\chi \approx 140 \text{ GeV}$$

MSSM DARK MATTER

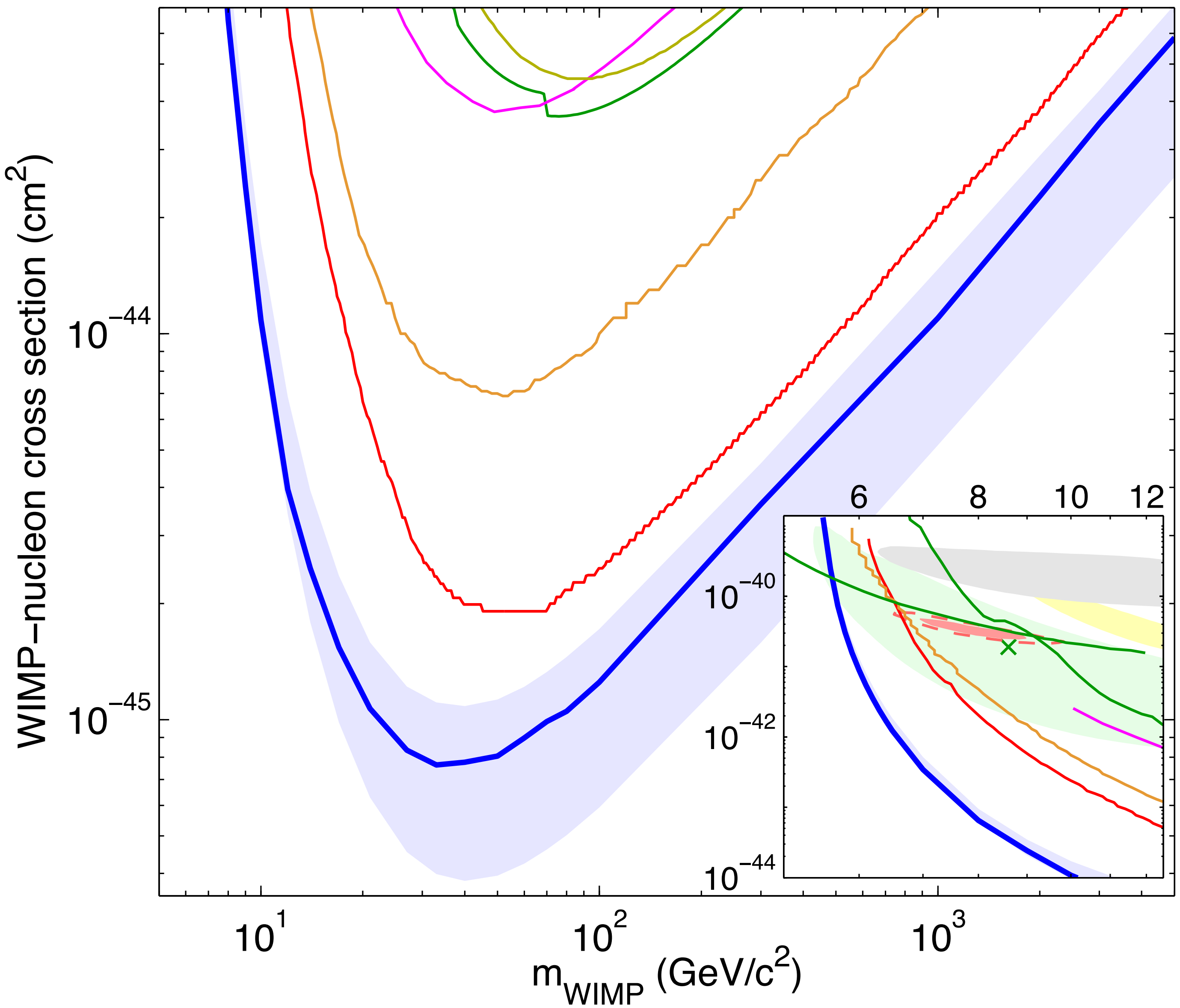
Bino: overpopulates, unless slepton is very light or degenerate within 5% for coannihilation.



Viable MSSM dark matter:
- **coannihilation** to boost relic abundance of a mostly-bino state
- delicate **mixing** of wino/higgsino and bino to get thermal abundance (“well-tempered”)
- **non-thermal relic abundance**

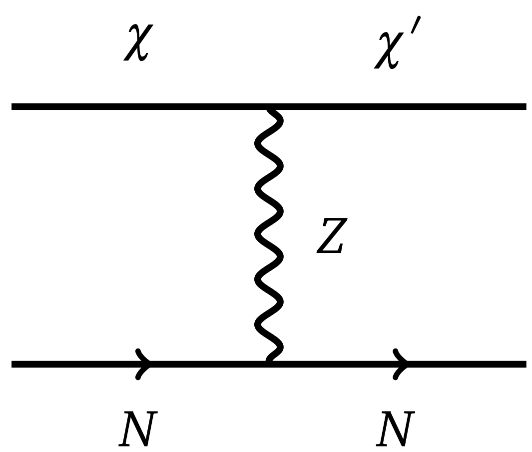
DIRECT DETECTION

LUX bounds are ruling out WIMP-nucleon cross sections of around 10^{-45} cm^2. What does this mean?



1310.8214

DIRECT DETECTION RATES



The first expectation might have been dark matter scattering with nuclei through a Z boson.

$$\sigma \gtrsim 5 \times 10^{-40} \mathrm{cm}^2$$

This was **ruled out** long ago. But only really applies to matter with purely chiral masses, like **fourth generation neutrinos**.

Generally, **X**, **X**' have at least *slightly* different masses; shut off this channel (or "inelastic dark matter").

DIRECT DETECTION RATES

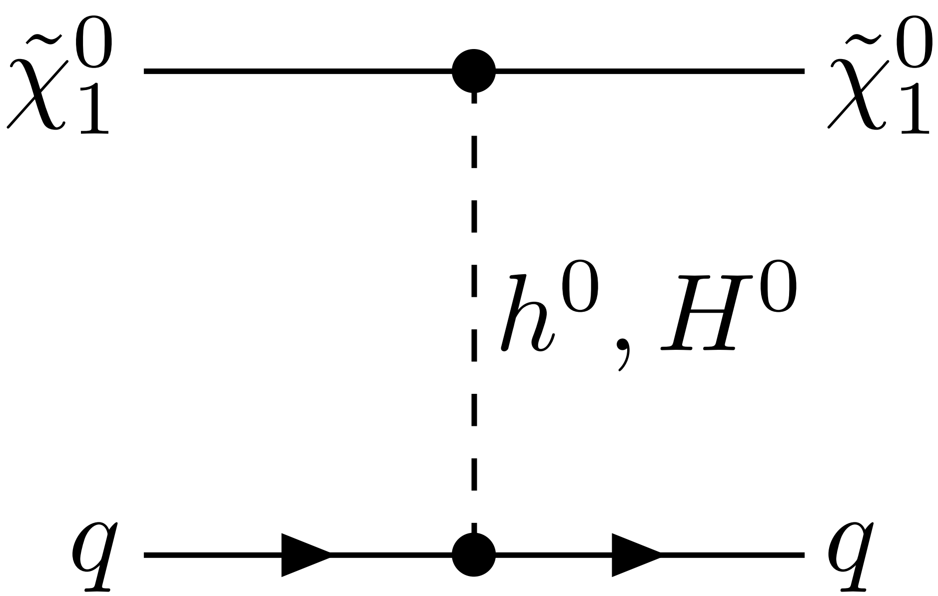
The next expectation is that DM can scatter with nuclei through a *Higgs boson*. Happens if DM gets part of its mass from the Higgs.

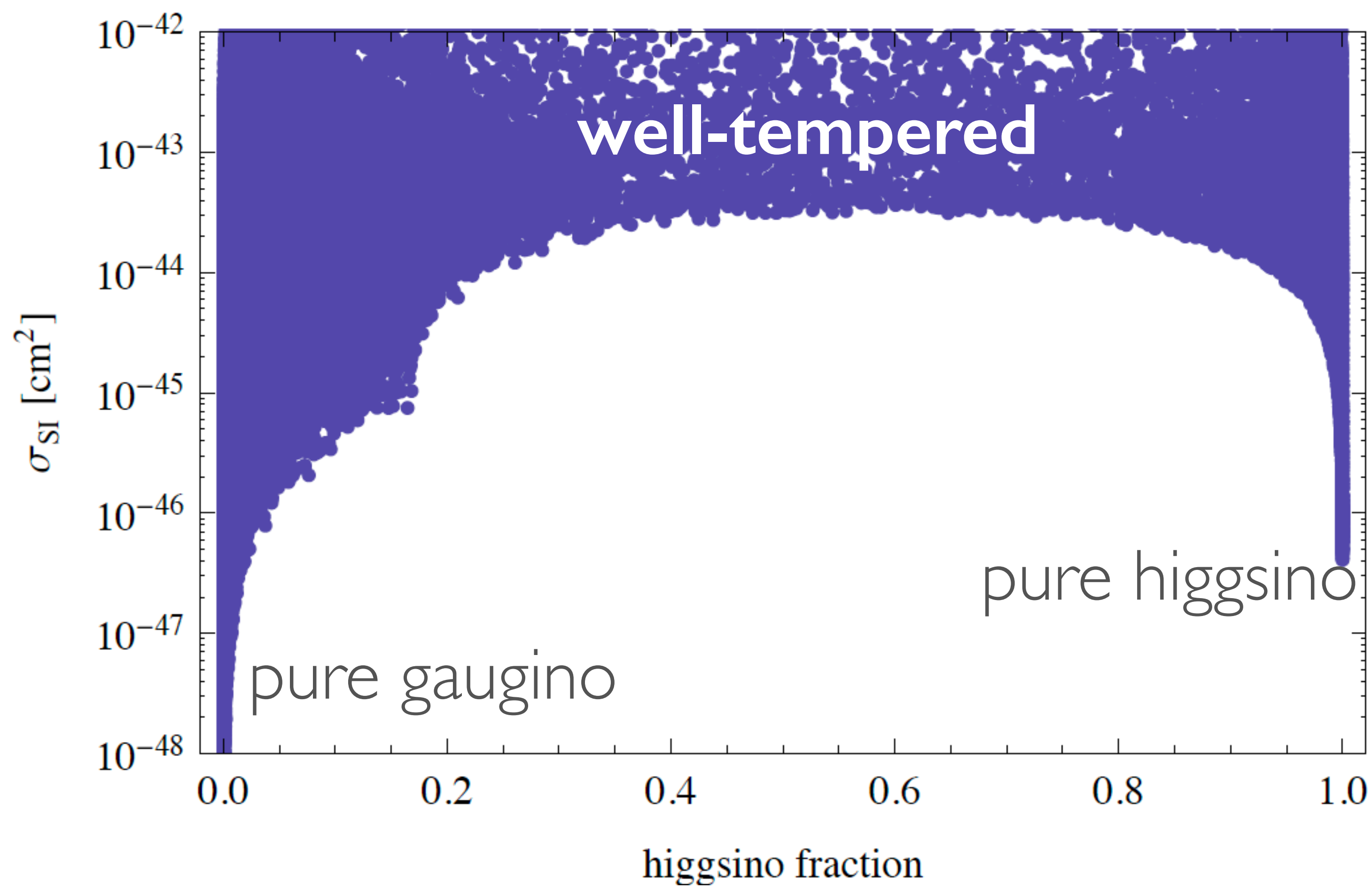
E.g. a scalar with quartic coupling $\lambda|S|^2|H|^2$:

$$\sigma \approx \lambda^2 \times \left(\frac{100 \text{ GeV}}{M_{\rm DM}}\right)^2 \times 3 \times 10^{-44} \text{ cm}^2$$

Higgs exchange is what experiments are probing now.

MIXED NEUTRALINO DM





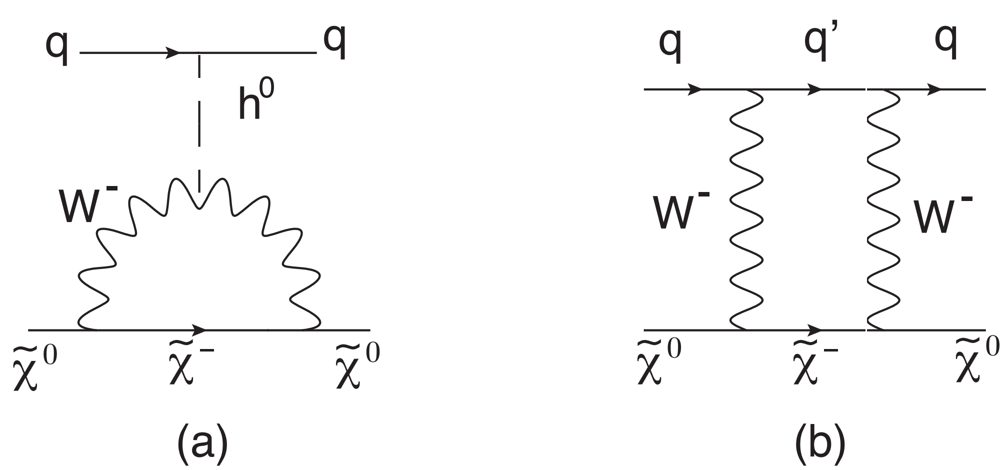
Rely on bino/higgsino/higgs or wino/higgsino/higgs couplings. **Pure higgsino or pure gaugino DM can evade detection.** *"Well-tempered"* halfway ruled out.

Perelstein and Shakya, 1107.5048

DIRECT DETECTION RATES

There can be weakly-interacting particles with neither Z- nor Higgs-mediated interactions, but with ***W* loops**.

E.g. supersymmetric "winos":



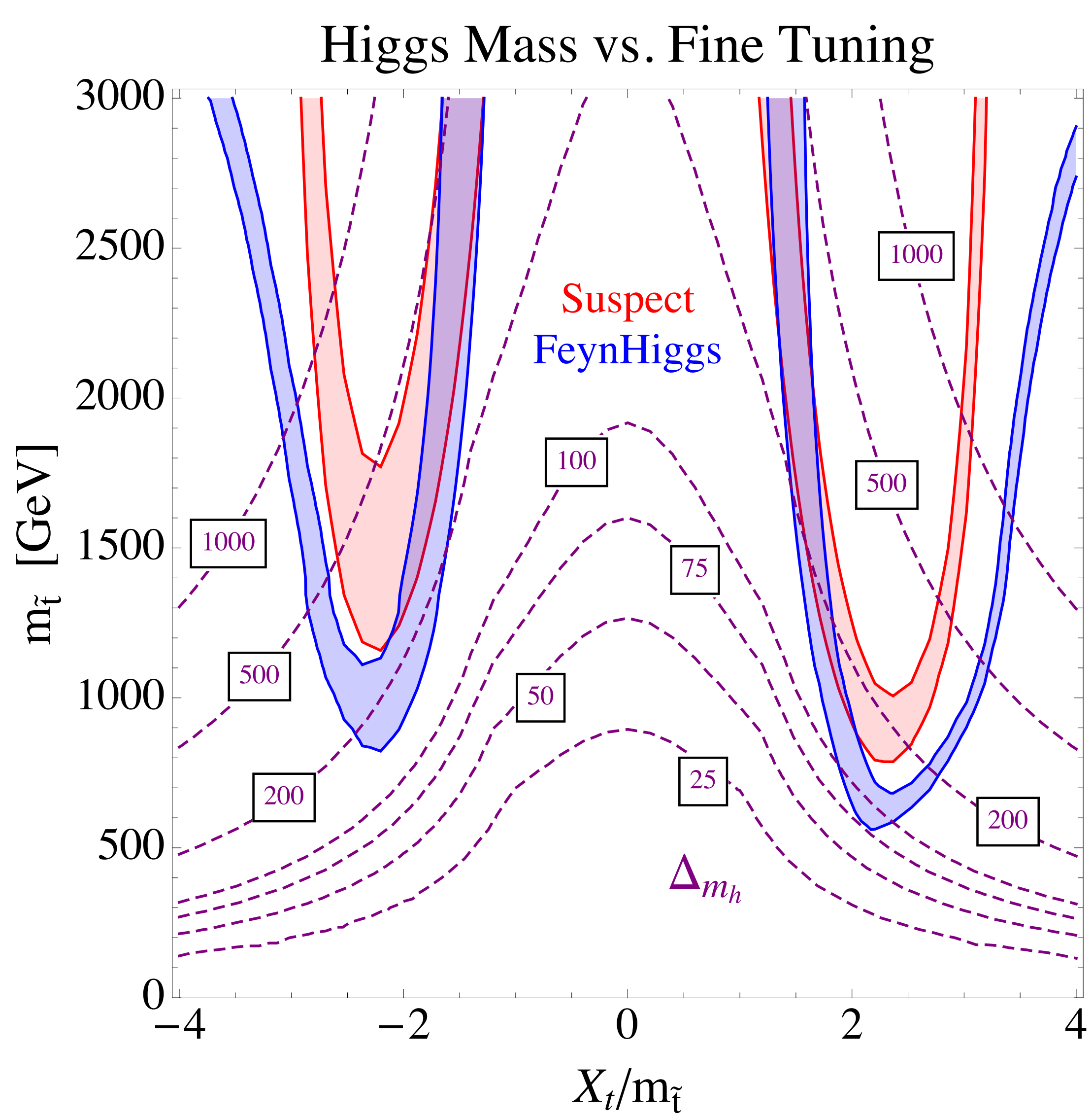
(beware sign mistakes leading to false optimism in earlier refs)

Hisano et al. 1004.4090 $\sigma \lesssim 10^{-47}\ \mathrm{cm}^2$

Down in the neutrino background. Even "WIMPs" may not show up at XENON!

125 GEV: MSSM IS UNNATURAL

In the MSSM, a 125 GeV Higgs mass requires heavy stops / large *A*-terms, but those **directly** undermine the naturalness argument for SUSY.



Tuning contours (Hall/Pinner/Ruderman 1112.2703) for **low-scale mediation**, $\Lambda = 10$ TeV

Always **at least** a factor of 100 tuning.

DICHOTOMY

Higgs at 125 GeV

Beyond MSSM,
natural

MSSM, tuned
with heavy
scalars

robust experimental connection

Stop search;
Higgs sector
(rates, decays)

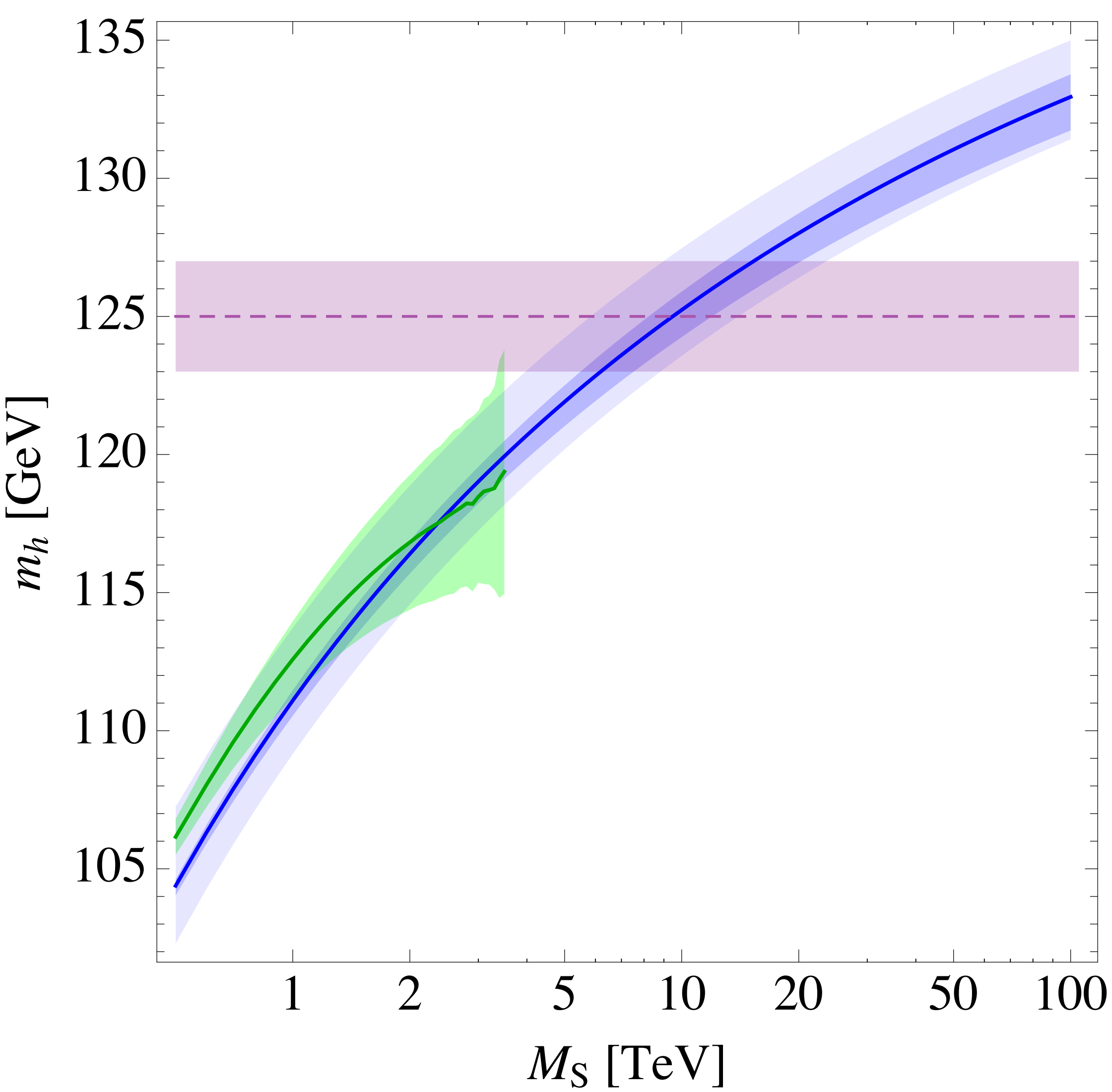
Models?
(NMSSM, D-terms,
compositeness....)

Gluinos;
Wino DM?

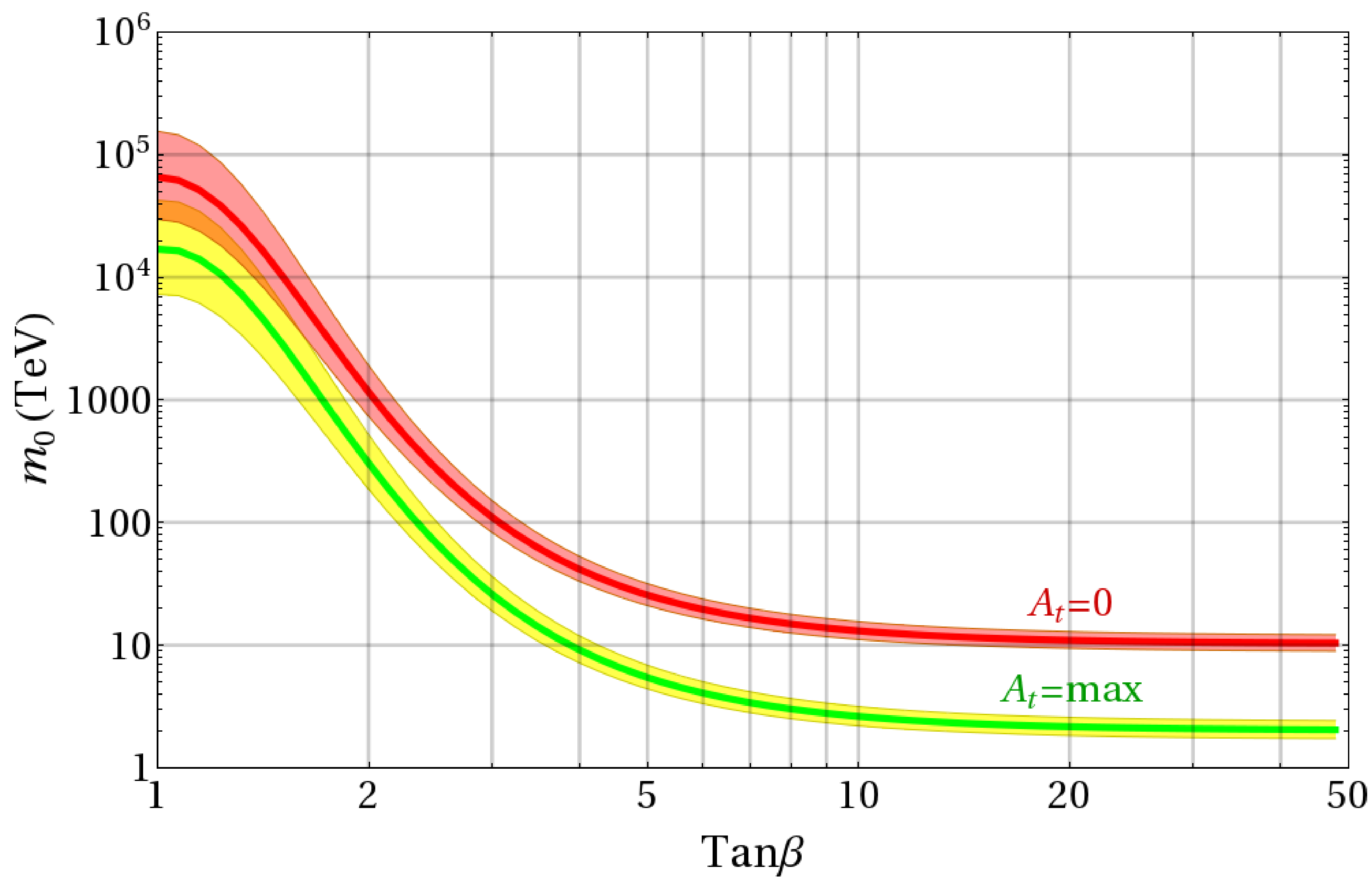
Top-down
theory

WHY SPLIT?

Arkani-Hamed & Dimopoulos originally had in mind very heavy scalars. But what the data points to now may be only "mildly" split SUSY, with scalars at 10s—100s TeV.



Draper, MR, Meade, Shih 1112.3068



Arvanitaki, Craig, Dimopoulos, Villadoro 1210.0555

ANOMALY MEDIATION AND MINI-SPLIT

The observed Higgs mass fits well with *anomaly mediation* or other scenarios (including many moduli-mediated scenarios) where gaugino masses are set by

$$m_\lambda \sim \frac{\alpha}{\pi} m_{3/2}$$

For plausible and typical models, in such a scenario scalars are ~ $m_{3/2}$ and the spectrum is split.

If gauginos are ~ TeV (and we know they aren't much lighter!), the scalars are in the right place for a 125 GeV Higgs. (1 TeV gluino means ~40 TeV gravitino & scalars)

MODULI

Moduli are scalar fields coupling with gravitational strength. In string constructions their VEVs determine couplings, e.g.

$$\mathcal{L} \supset c_\phi \frac{\phi}{M_{\rm Pl}} F_{\mu\nu} F^{\mu\nu}$$

These fields are often light: the natural scale for their masses is $\sim m_{3/2}$. (Coughlan, Fischler, Kolb, Raby, Ross 1983; de Carlos, Casas, Quevedo, Roulet 1993).

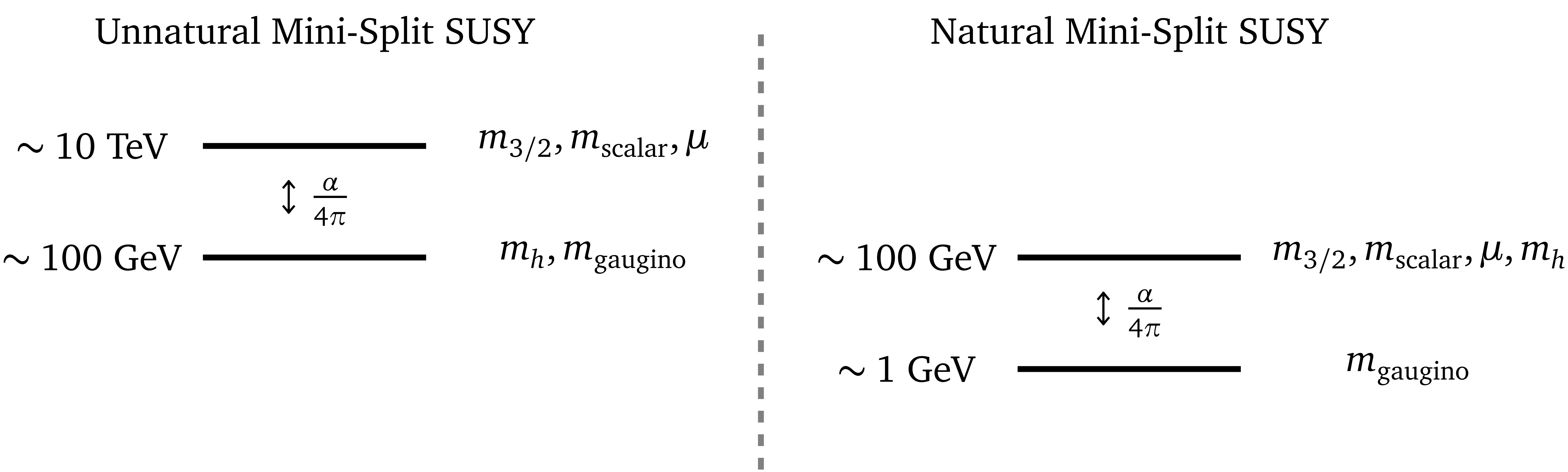
Overclose the universe or ruin BBN unless their masses are $> (T_{BBN}^2 M_{Pl})^{1/3} \sim 100$ TeV. **There's the 100 TeV scale again!**

TRIPLE COINCIDENCE?

- If gauginos are at the 100 GeV to 1 TeV scale (and we know they aren't much lighter…), AMSB puts the gravitino at ~10 to 100 TeV.
- If we want moduli to reheat above BBN, this picks out a scale ~10 to 100 TeV.
- If we want to raise the Higgs mass to 125 GeV without large A-terms, for moderate to large tan beta this picks out scalar masses ~ 10s of TeV.
- It's a nice story, aside from the fine-tuning.

THE ANTHROPIC QUESTION

Our picture raises a question: SUSY could have been split *and* natural.



Is there a good reason why we might find ourselves living in the universe at left instead of the natural one at right?

Maybe an anthropic answer involving ***moduli cosmology*** (work in progress with Josef Pradler).

A BIG PICTURE?

SUSY may solve most of the hierarchy problem. What we see conflicts with our notions of naturalness because we could not live in the natural world. Balance of two pressures:

GEV → **We are here?** ← Planck scale

Anthropic pressure | **Naturalness pressure**

Sounds philosophical, but the hope is for an anthropic story that relates to cosmology in a predictive way. Still work in progress….

NONTHERMAL DARK MATTER

Considering moduli cosmology motivates pairing **semi-split SUSY** with **nonthermal dark matter** generated through moduli decay.

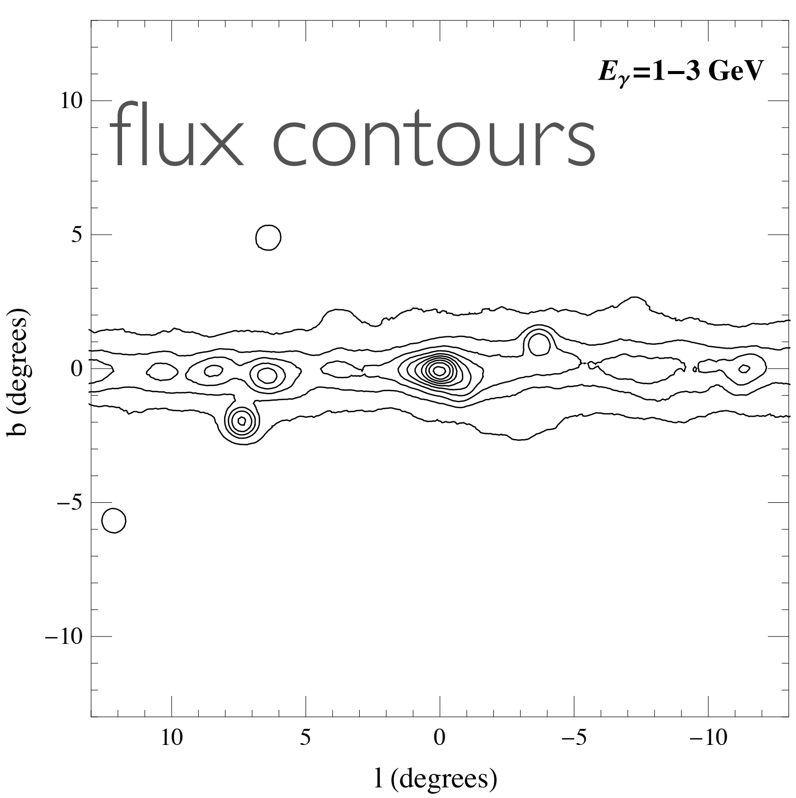
see: Moroi/Randall hep-ph/9906527; J. Kaplan hep-ph/0601262; Gelmini/Gondolo hep-ph/0602230, Acharya/Kumar/Bobkov/Kane/Shao/Watson 0804.0863, others....

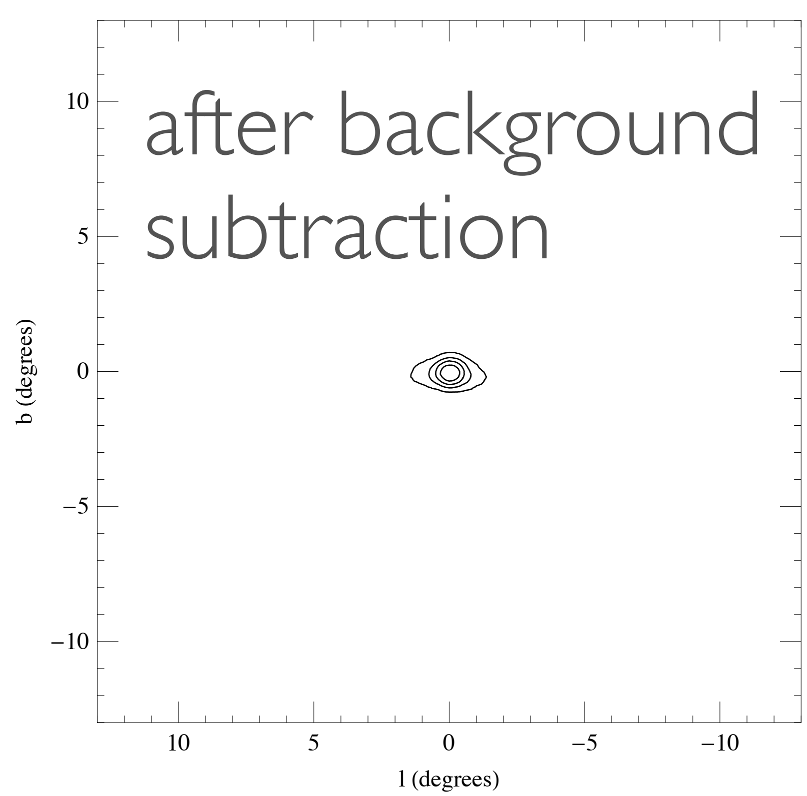
For given $\langle\sigma v\rangle$, DM abundance is enhanced by a factor of $T_{freezeout}/T_{RH}$. **Ideal for light wino DM**, with large annihilation rate.

ANNIHILATING DARK MATTER

Expect a flux of gamma rays related to the square of the integral along the line of sight:

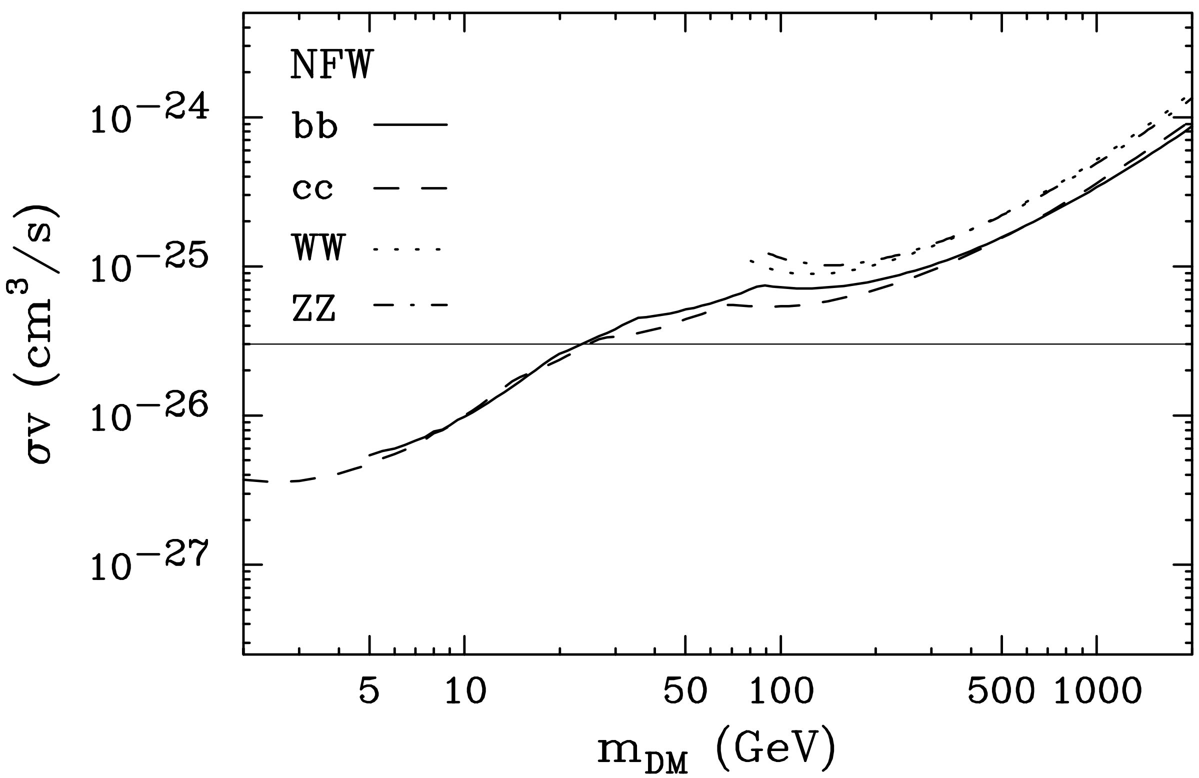
$$\Phi(\psi) = \frac{\sigma v}{8\pi m_{\mathrm{DM}}^2} \frac{dN_\gamma}{dE_\gamma} \int_{\mathrm{los}} \rho^2(l)\,dl$$

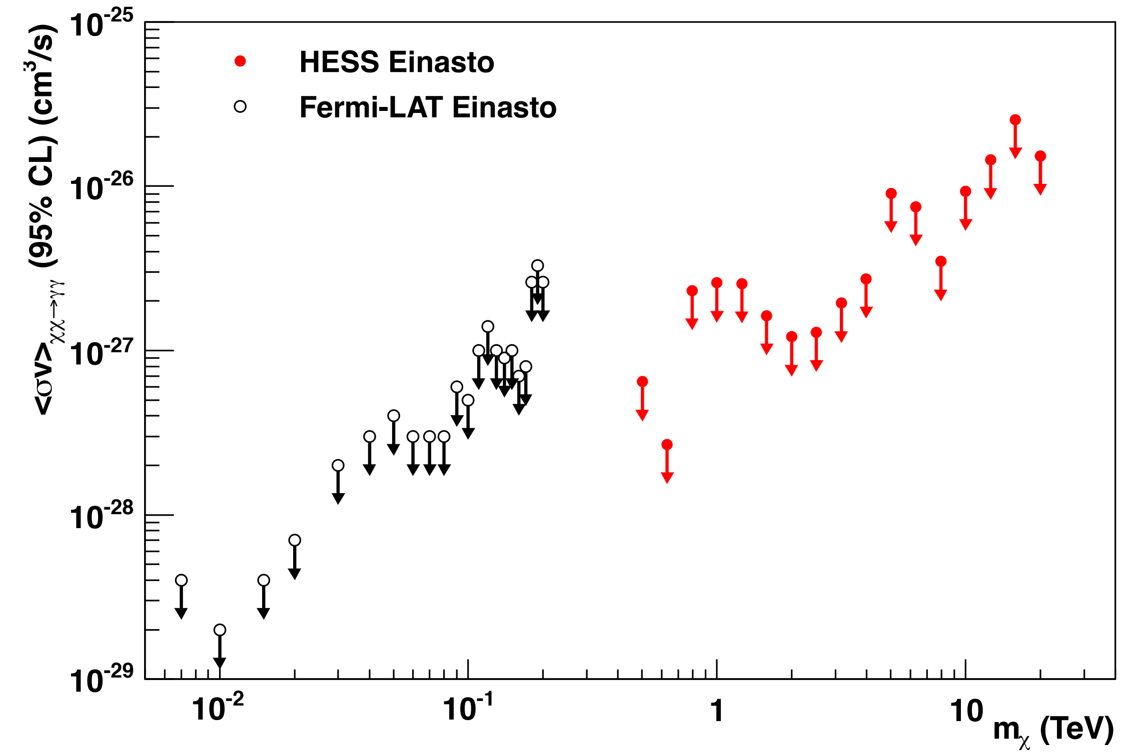




Best signal near the galactic center, but lots of background all along the plane (Hooper, Kelso, Queiroz1209.3015)

BOUNDS FROM FERMI-LAT AND HESS



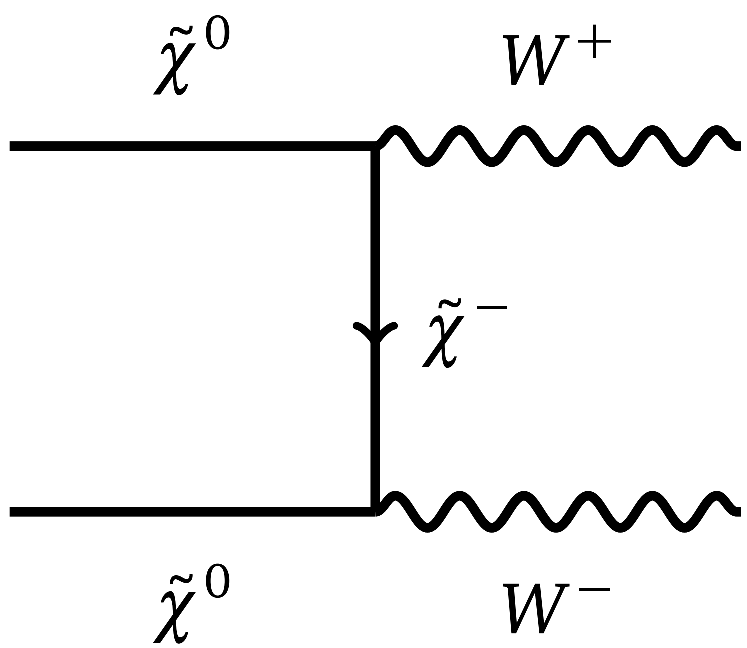


Galactic center continuum bound, Hooper et al.

HESS line search, 1301.1173

(Fermi dwarf bounds weaker)

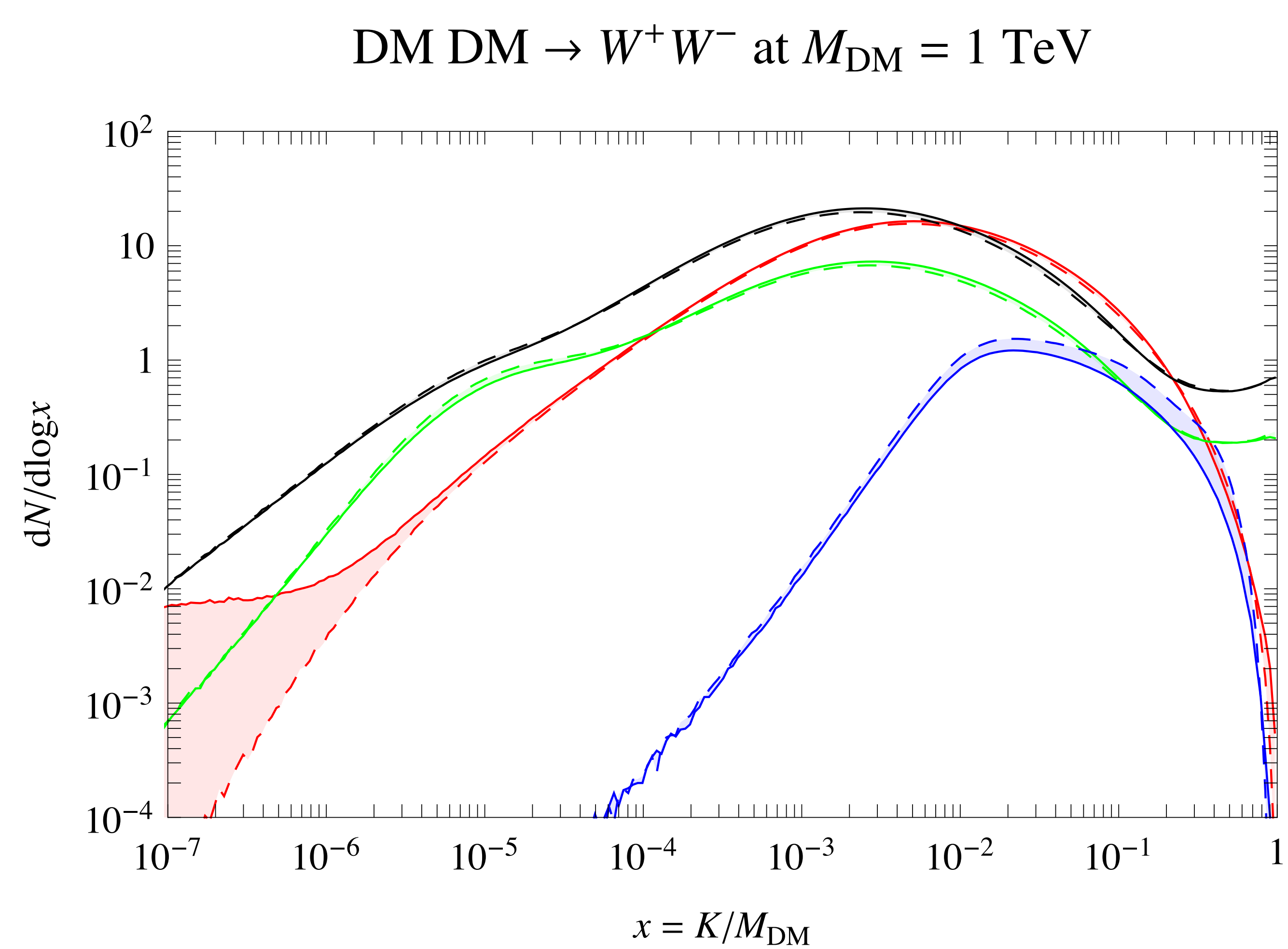
CONTINUUM GAMMAS FROM WINO ANNIHILATIONS



Winos annihilate through the weak interaction to W bosons. Gamma rays mostly from pions.

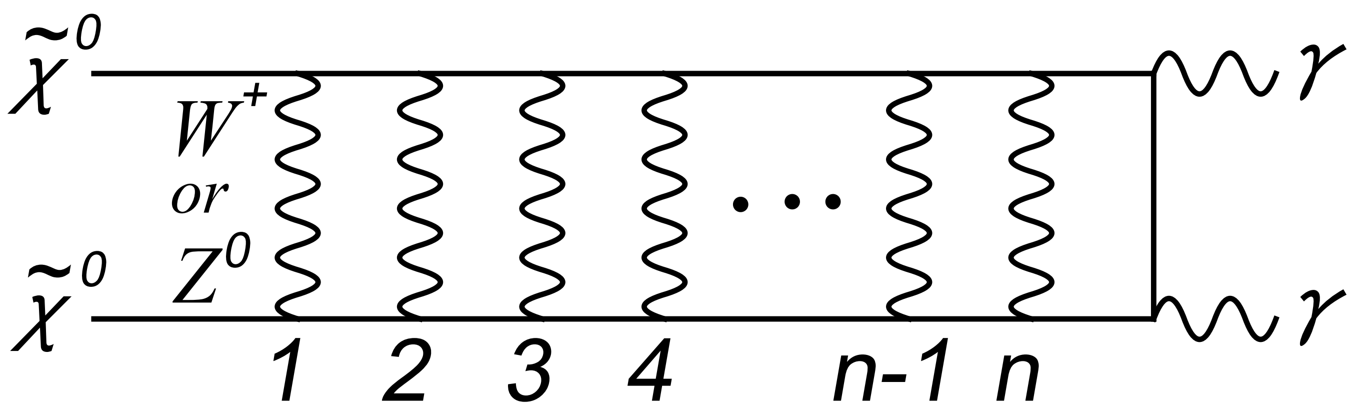
Cirelli et al 1012.4515: red curve is photons. Peak at energies ~ $M_{DM}/100$

(black: neutrinos; green: e+/e-; blue: antiprotons)



SOMMERFELD ENHANCEMENT

For heavy winos, the rate can be very enhanced (Hisano et al '04)

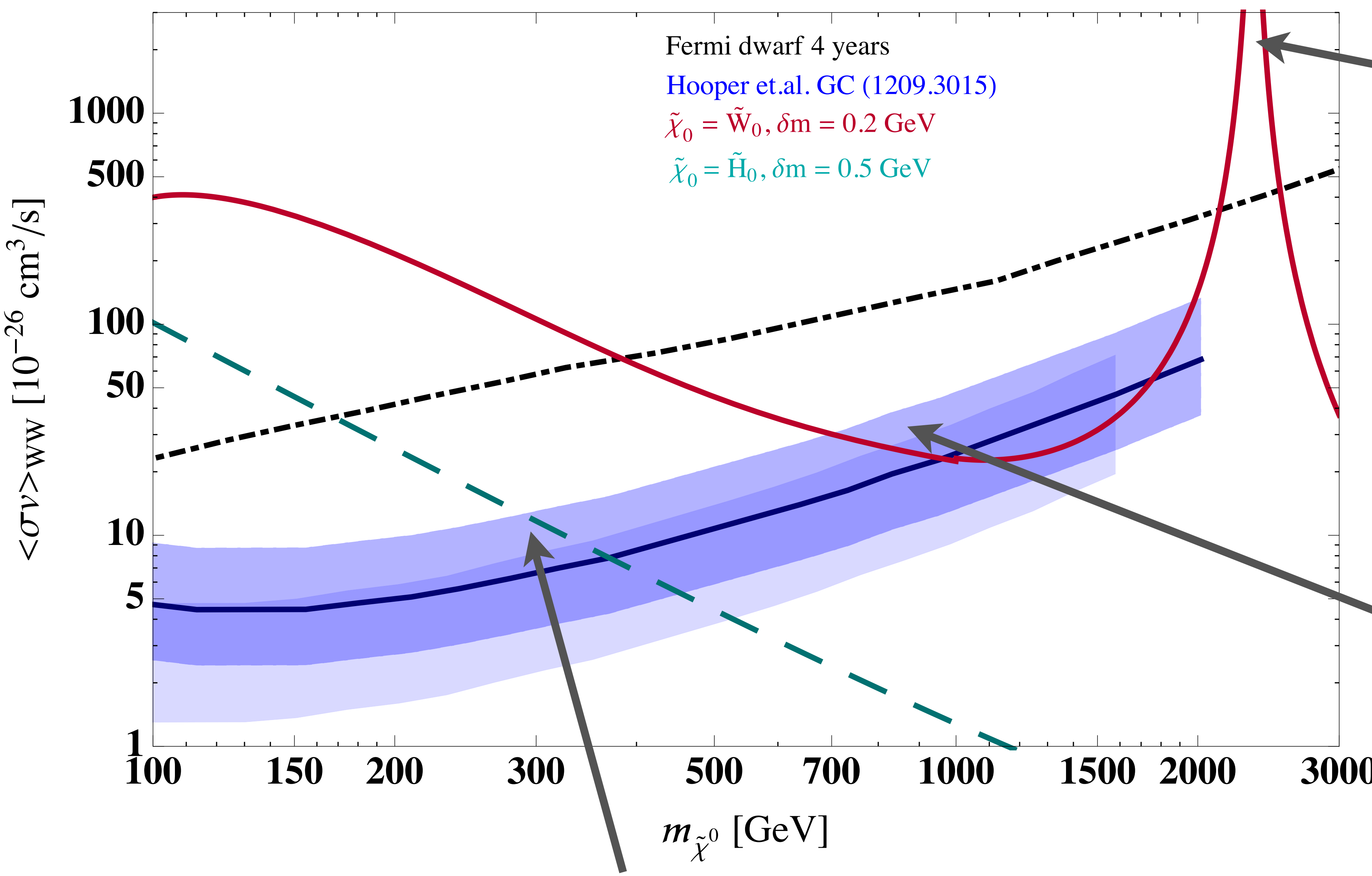


This is because, relative to the scale set by the wino mass, *W* exchange becomes a long-range force. Resonant peaks where bound states form.

Tiny tree-level charged/neutral splitting: $\delta m_{\mathrm{tree}} \simeq \frac{m_Z^4}{M_1 \mu^2} s_W^2 c_W^2 \sin^2 2\beta$

Loop splitting usually dominates: ~ 160 MeV

CONTINUUM BOUNDS

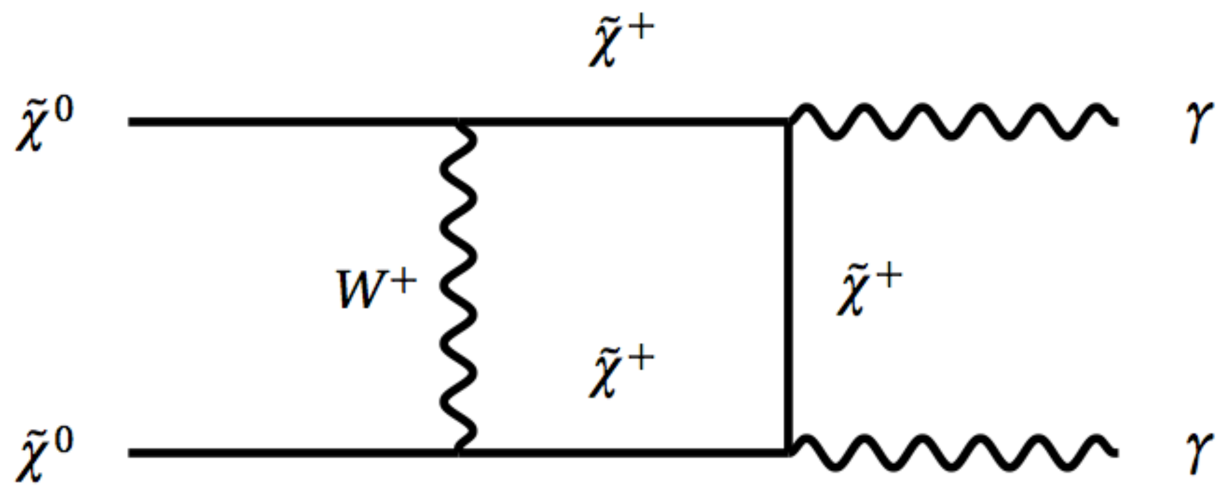


resonant peak (Sommerfeld)

winos excluded to at least ~700 GeV

higgsinos excluded to ~300 GeV

GAMMA-RAY LINES

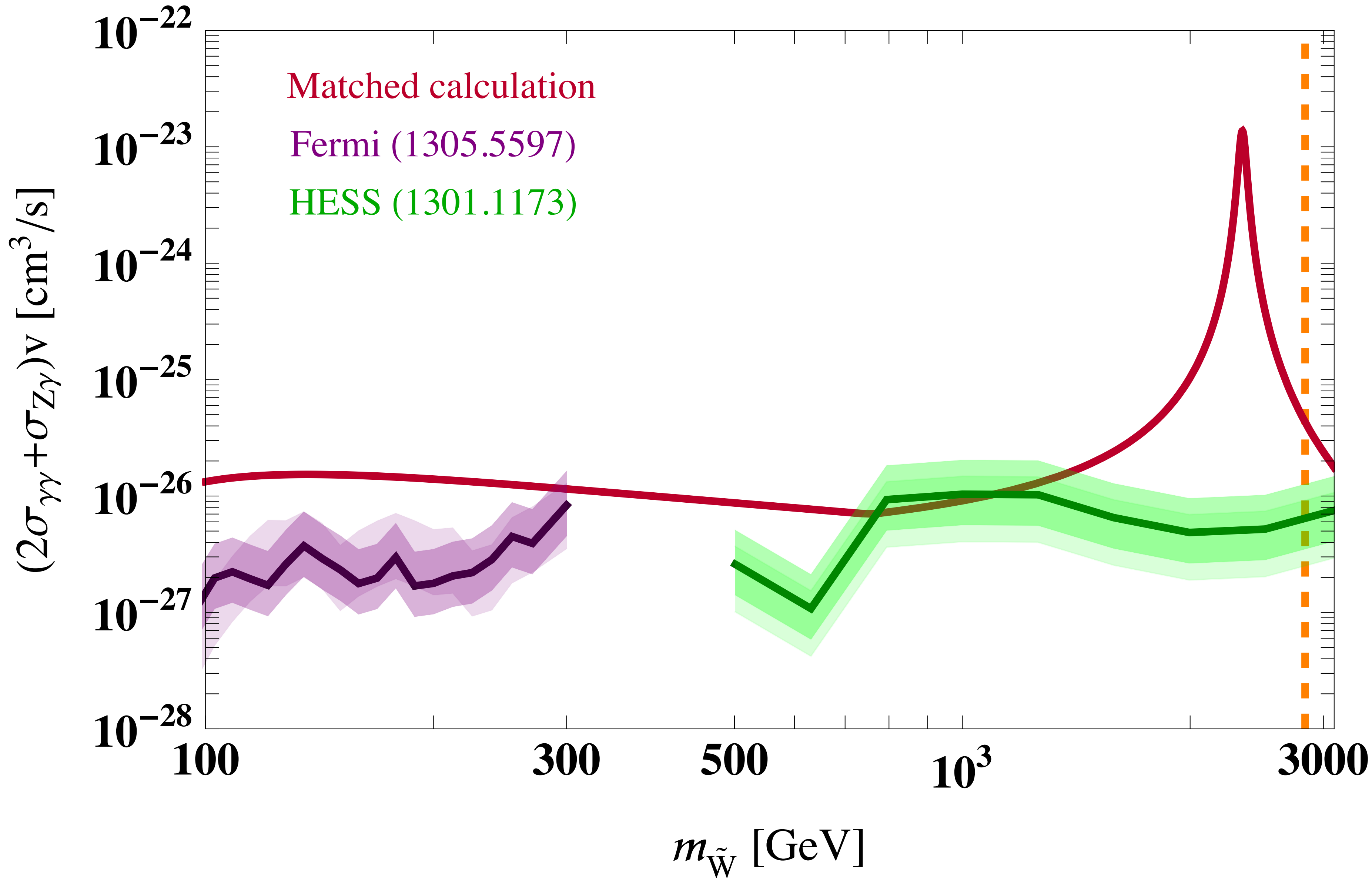


Naively, down by a loop factor, so less useful than continuum.

However, at large wino mass this goes as $\sim 1/m_W^2$, not $1/m_{wino}^2$ (closely related to Sommerfeld effect).

Thus, line searches are a very powerful probe of heavy winos.

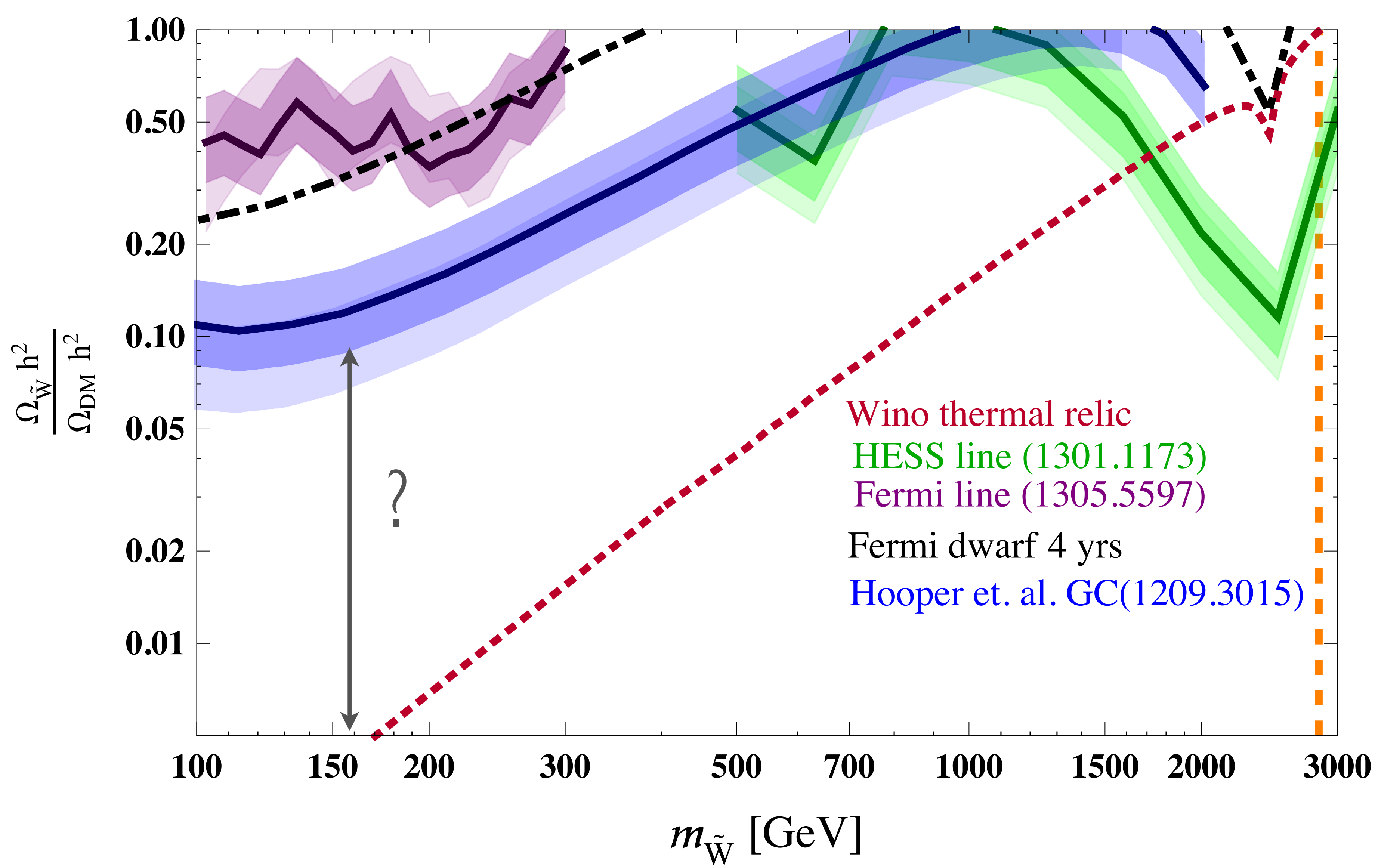
LINE BOUNDS



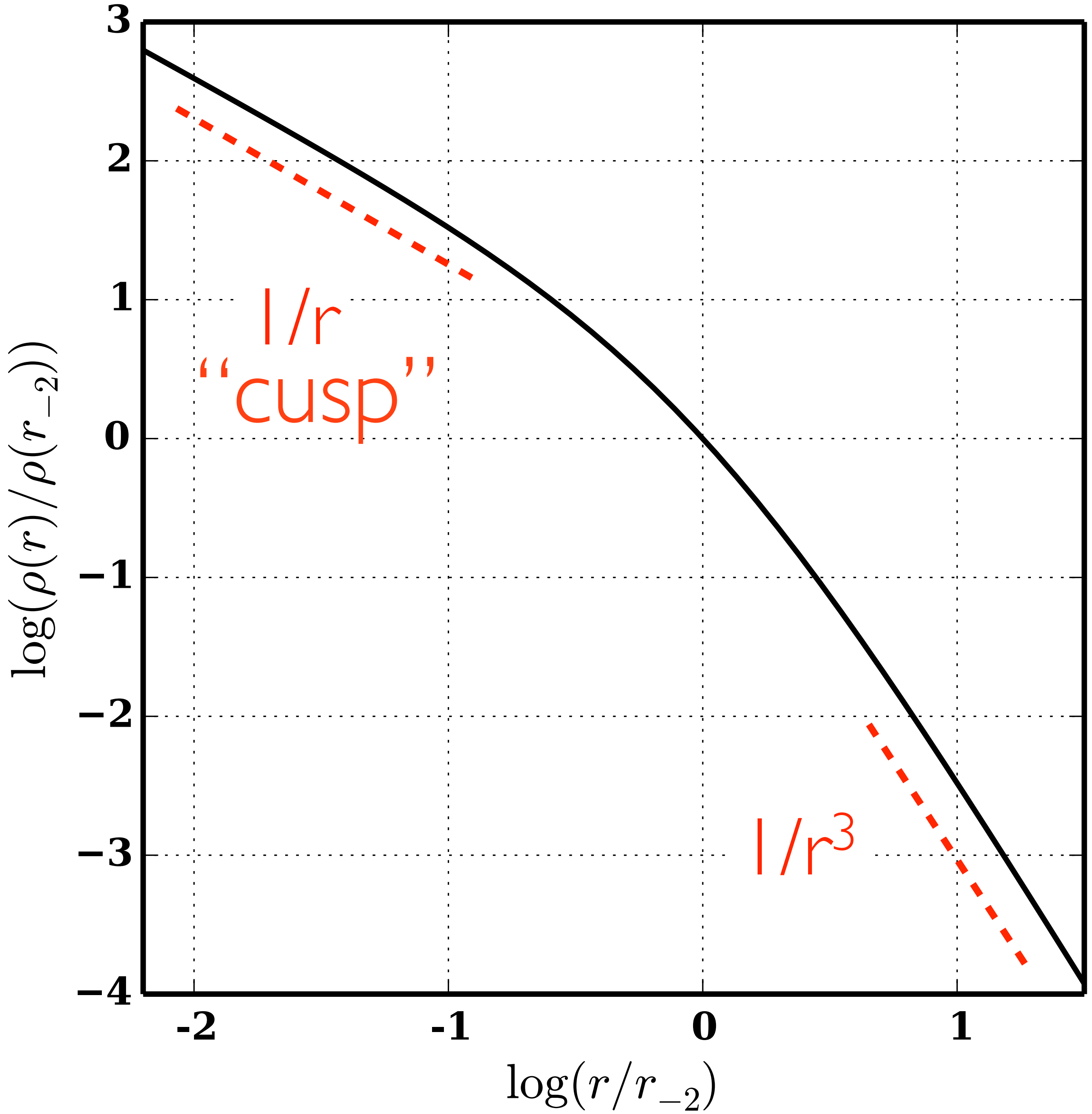
HESS excludes most of the high-mass region (including thermal winos). Fermi excludes low masses, again.

FRACTION OF ALLOWED WINO DARK MATTER

still a way to go before ruling out a subdominant *thermal* light wino



CONCENTRATION OF DM IN THE GALACTIC CENTER?

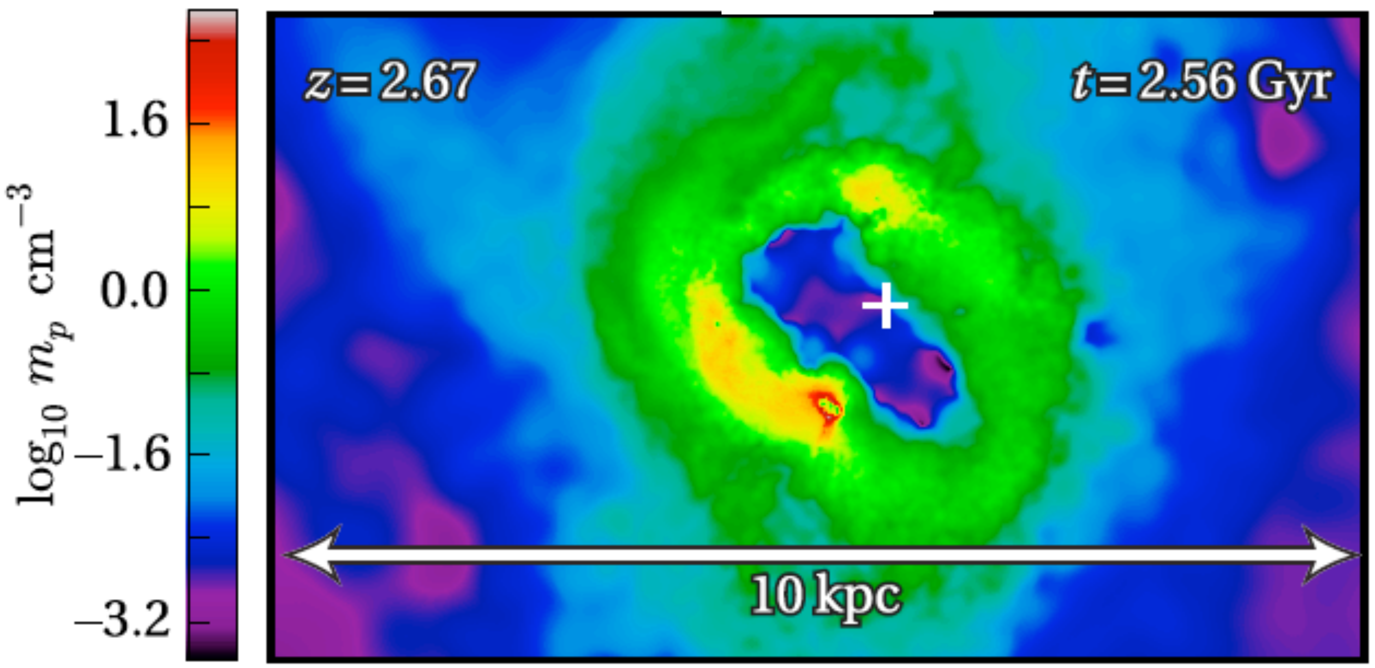


NFW profile (Navarro, Frenk, White 1993)

Robust outcome of *N*-body simulations of *dark matter only*.

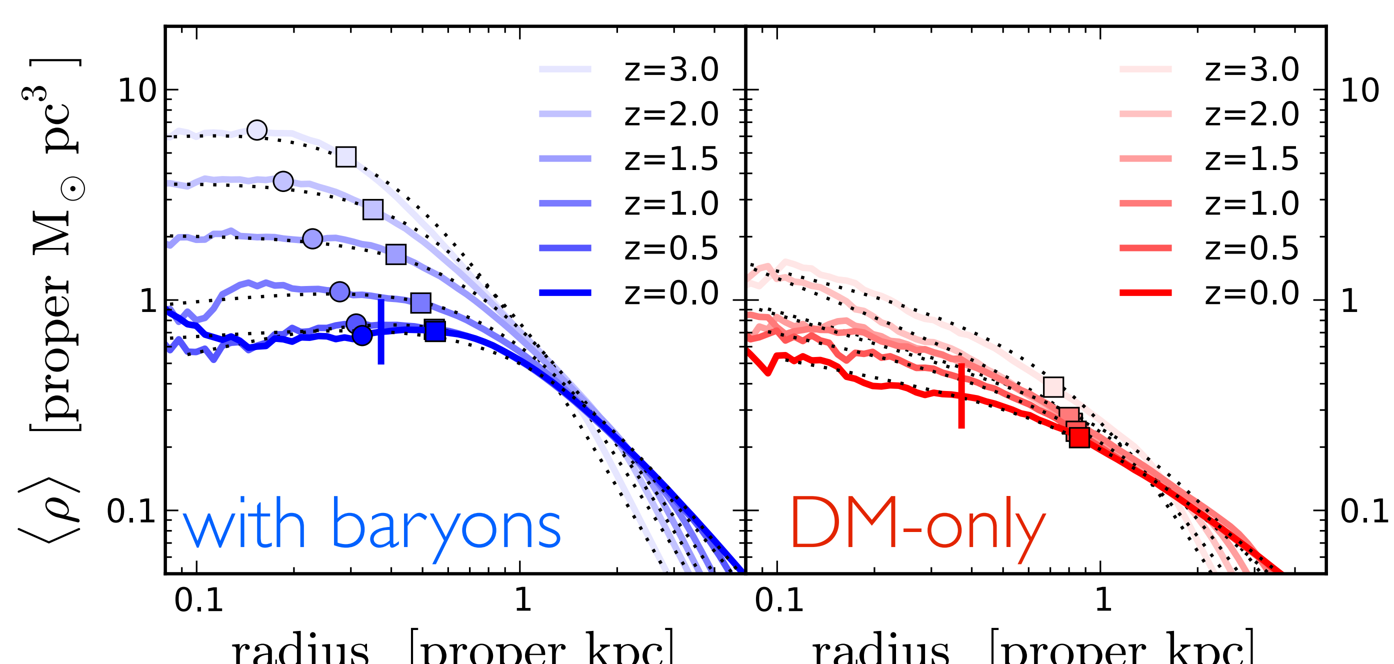
Does it apply in the real world?

DARK MATTER CORES FROM BARYONIC EFFECTS?

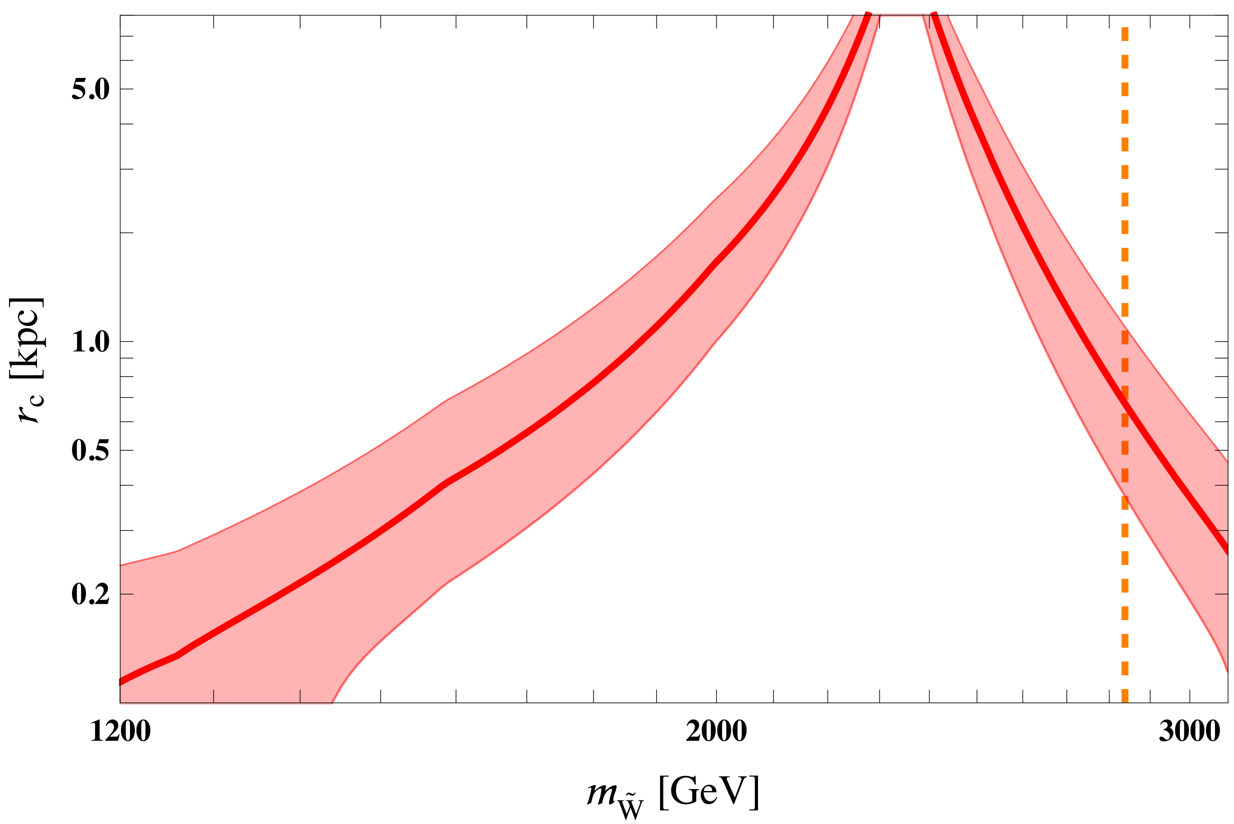


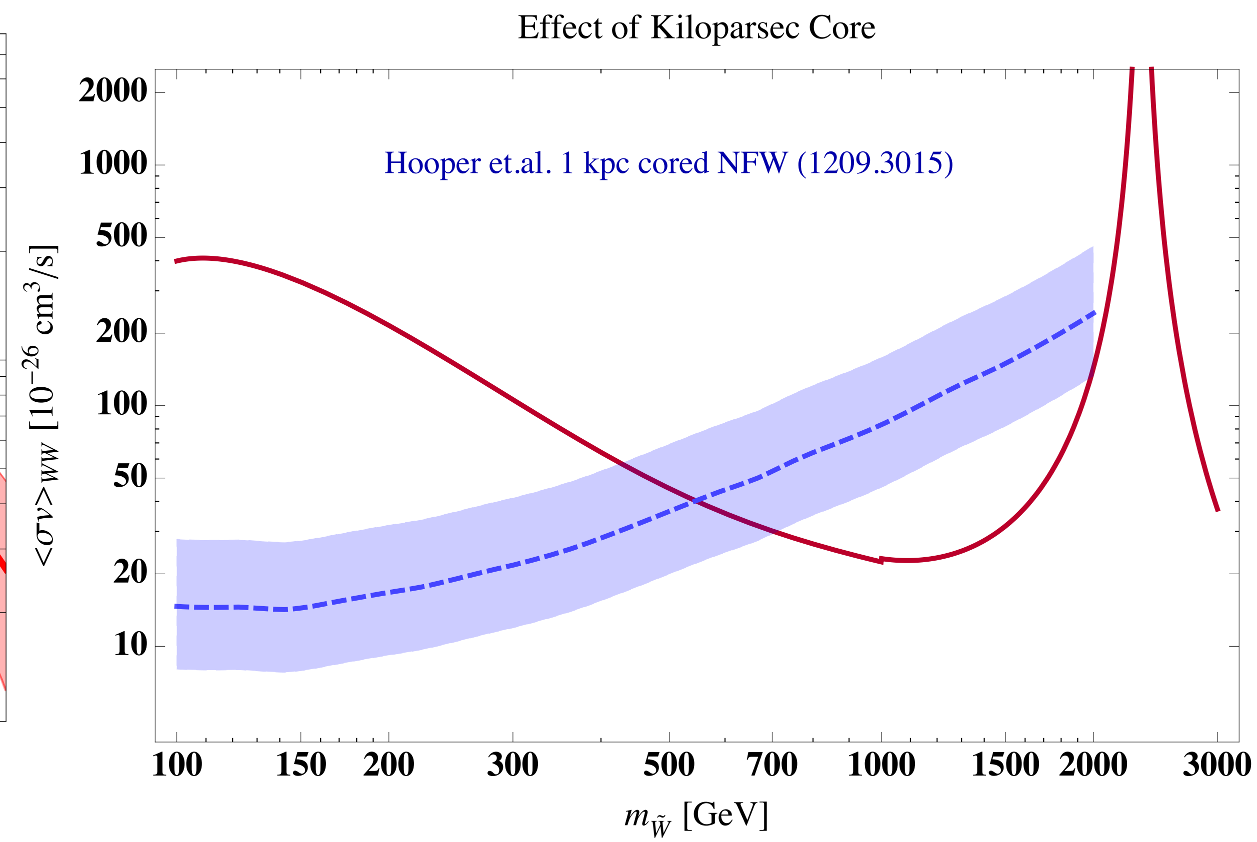
Pontzen/Governato 1106.0499: underdense bubble from supernova explosions.

Kuhlen et al. 1208.4844 bar/halo interactions?



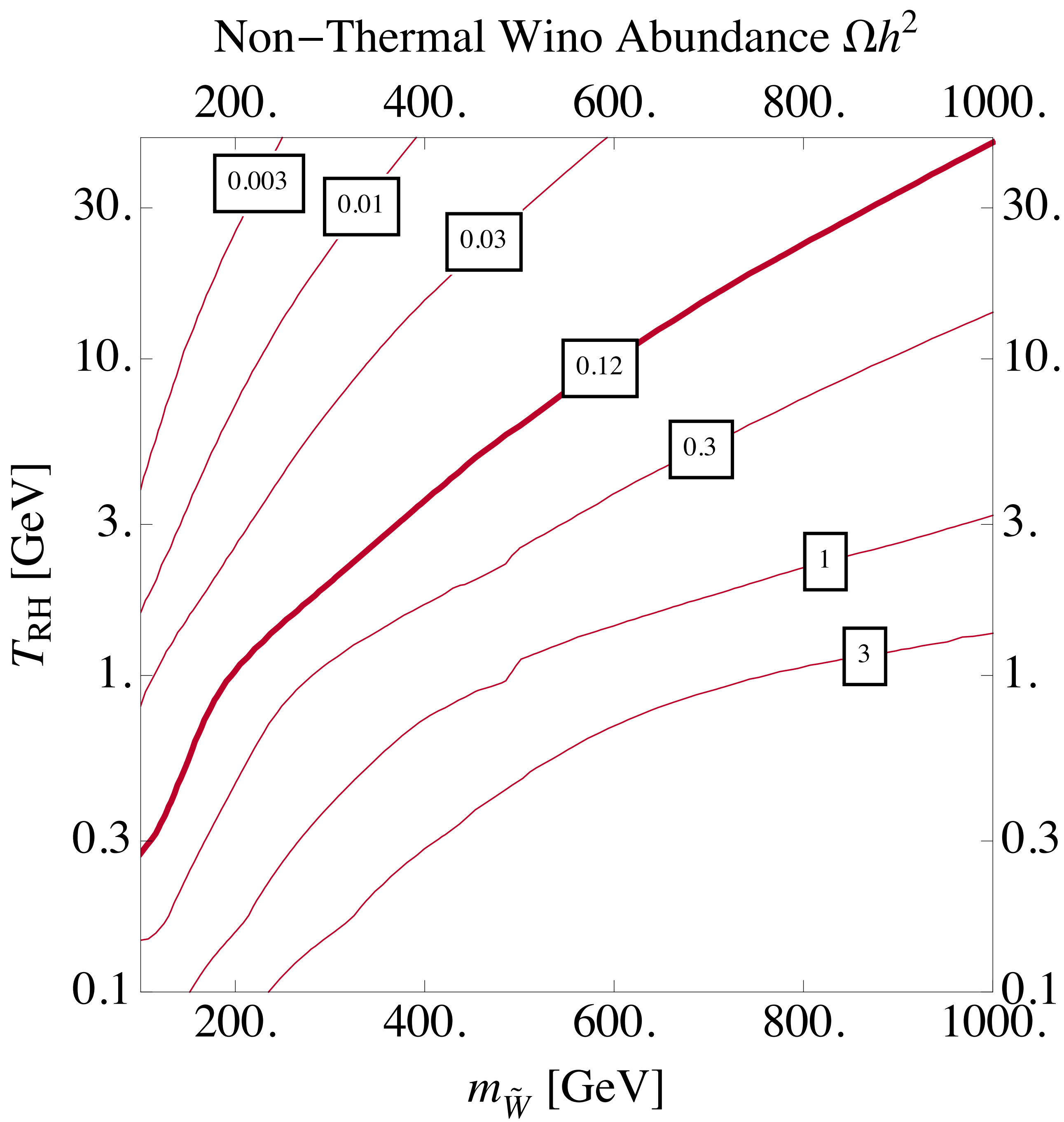
LIMITS WITH CORED DARK MATTER PROFILES





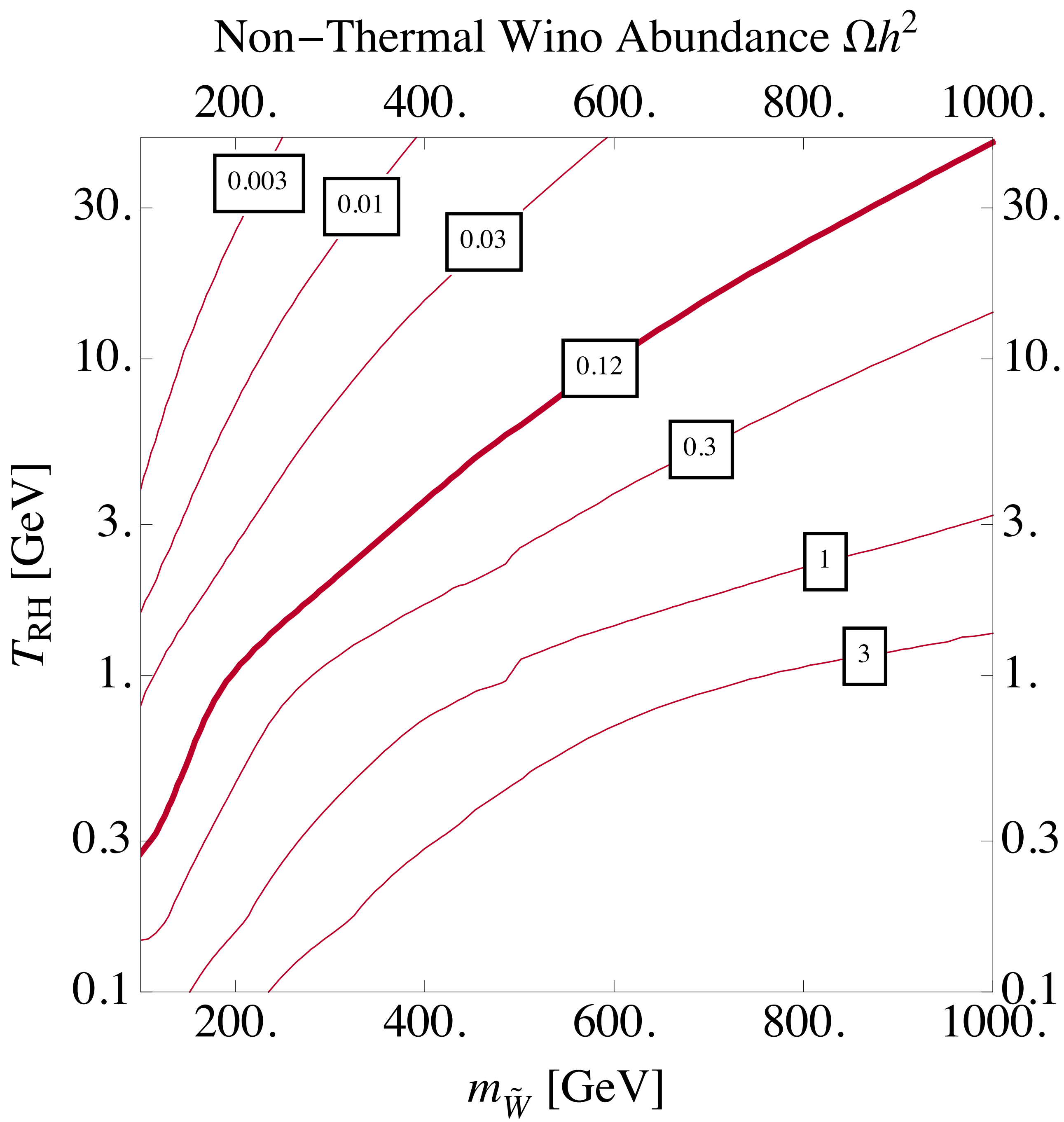
The thermal wino bound can be evaded with a ~ kpc core. *Even with* a kpc core, light winos cannot be all the DM for wino masses below ~400 GeV.

NON-THERMAL ABUNDANCES



Light wino LSPs (e.g. from anomaly mediation) are bad dark matter candidates *unless* we have exactly the sort of non-thermal cosmology moduli could provide. (Moroi & Randall, recently Gordy Kane & collaborators, Yanagida & collaborators, etc)

NON-THERMAL ABUNDANCES

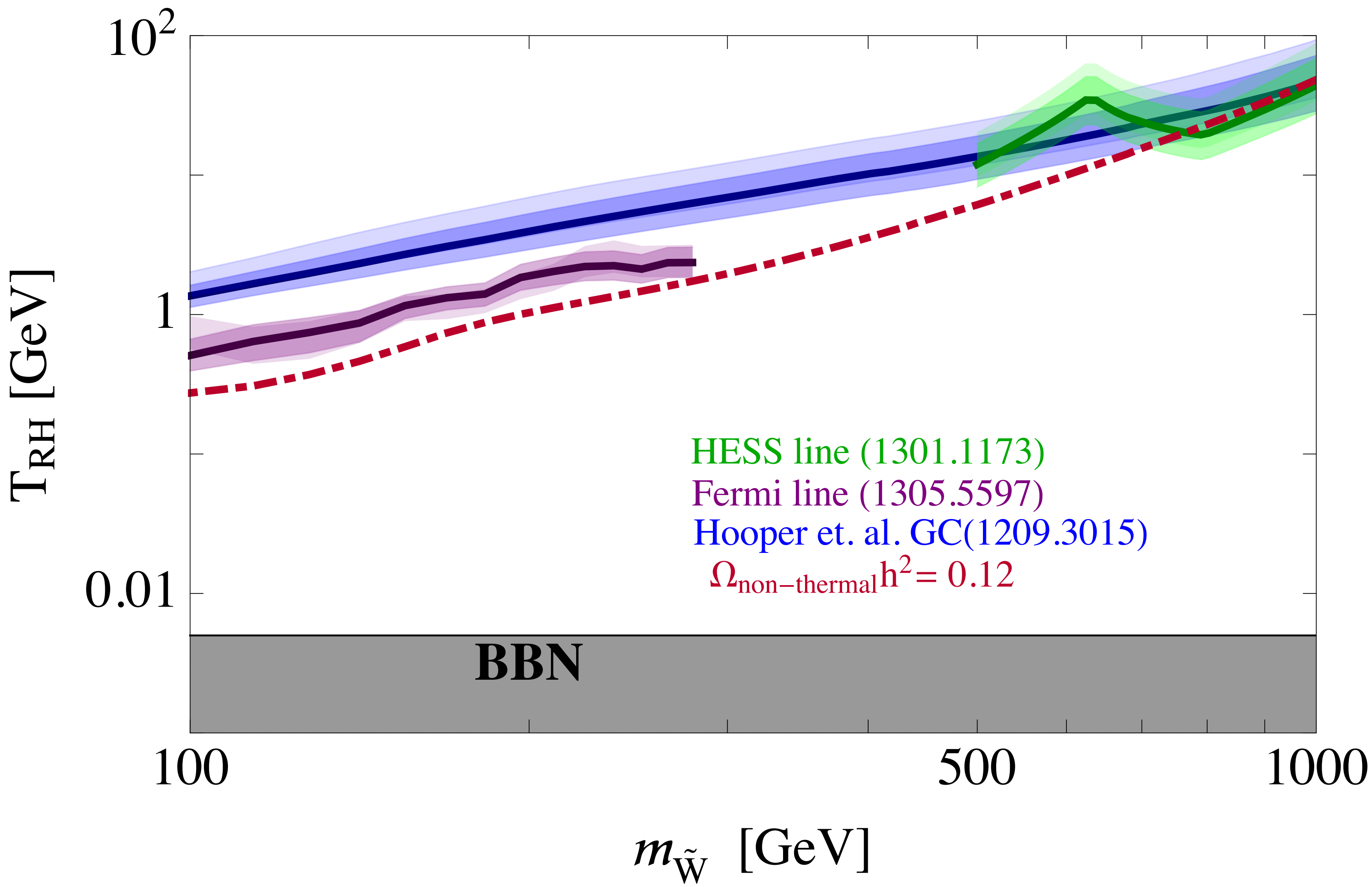


Solve a set of Boltzmann equations:

$$\begin{aligned}
\frac{dn_{\tilde W}}{dt} + 3Hn_{\tilde W} &= -\langle\sigma_{\rm eff} v\rangle(n_{\tilde W}^2 - n_{\tilde W,\rm eq}^2) + N_{\tilde W}\Gamma_X n_X, \\
\frac{dn_X}{dt} + 3Hn_X &= -\Gamma_X n_X, \\
\frac{d\rho_{\rm rad}}{dt}\left(1 + \frac{1}{3}\frac{\partial \ln g_*}{\partial \ln T}\right) &= (-4H\rho_{\rm rad} + q)\left(1 + \frac{1}{4}\frac{\partial \ln g_*}{\partial \ln T}\right),
\end{aligned}$$

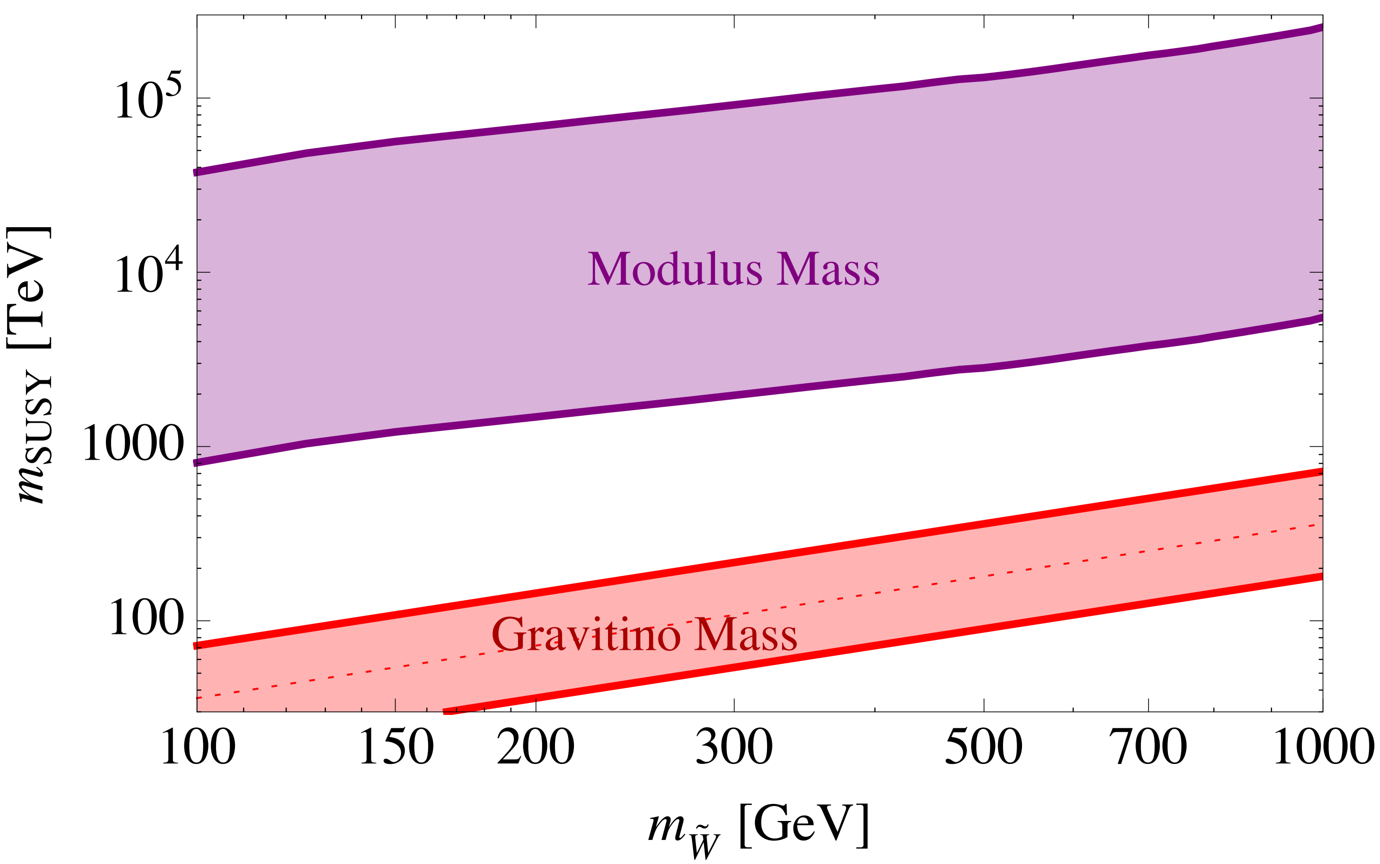
100 GeV winos are all the DM for reheat temperatures ~ 300 MeV.

BOUNDS ON THE REHEAT TEMPERATURE



Only reheat temperatures above about 1 GeV are allowed.

TROUBLE FOR MODULI COSMOLOGY?



Purple band:

$$\Gamma_\phi \sim \frac{m_\phi^3}{M_{\mathrm{Pl}}^2}$$

with plausible range of coefficients.

Red band: gravitino mass, if wino mass is ~ AMSB size.

Problem: moduli decays to gravitinos will overclose the universe.

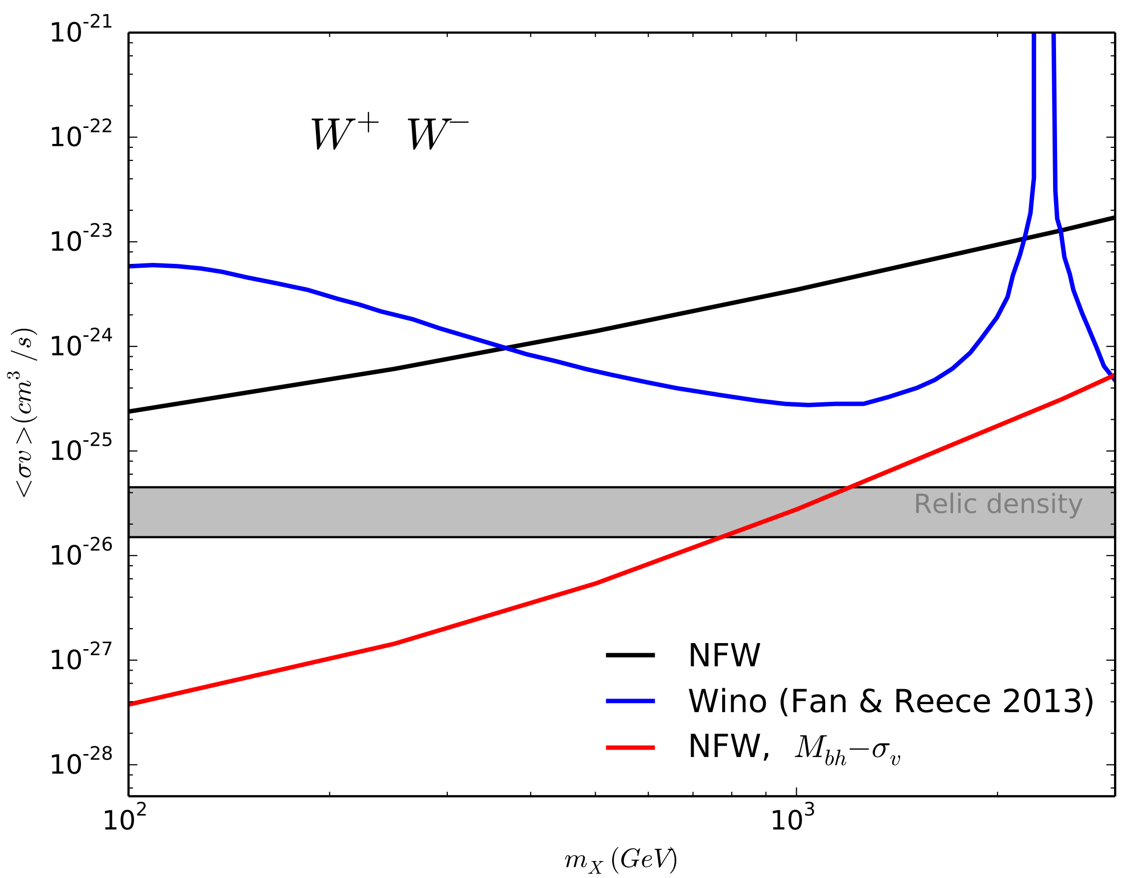
REFINEMENTS / CONCERNS

Fermi-LAT continues to take data. HESS II is also operating. So bounds will keep improving.

Would be nice to see tighter constraints on the DM distribution in the Milky Way. Not so easy near the Galactic Center because it's baryon dominated. But many star surveys (APOGEE, SEGUE, RAVE, Gaia, …) giving us data. How do we make the most of it?

Could DM distribution be off-center? Do we need to allow for that too?

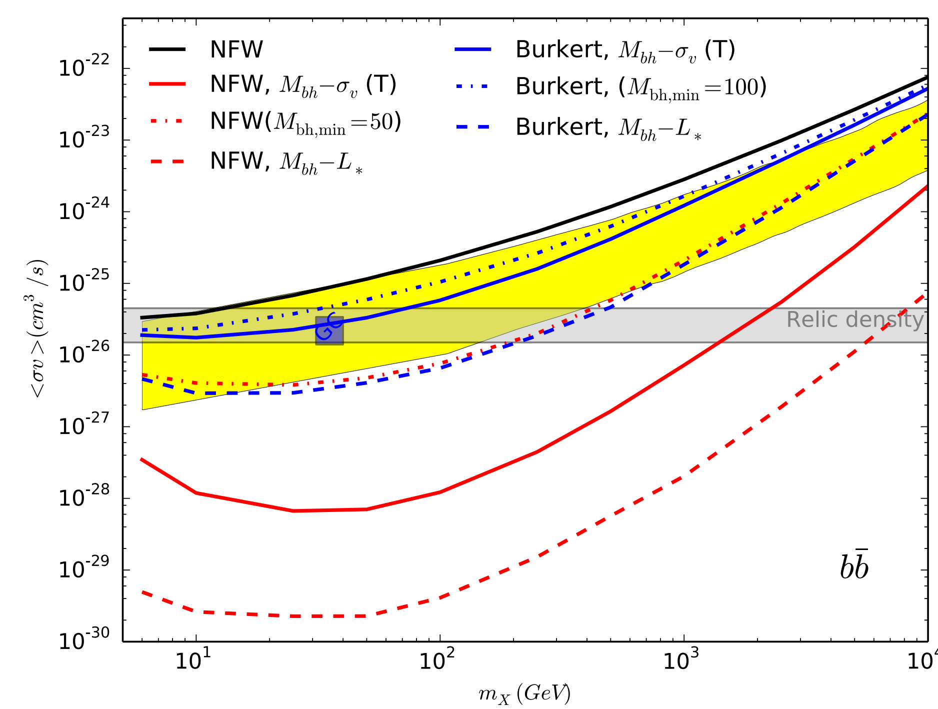
DM DISTRIBUTION IN DWARFS: SPIKY?



Gonzalez-Morales, Profumo, Queiroz 1406.2424

Density spikes near black holes? Huge uncertainties, but potentially *much* tighter bounds.

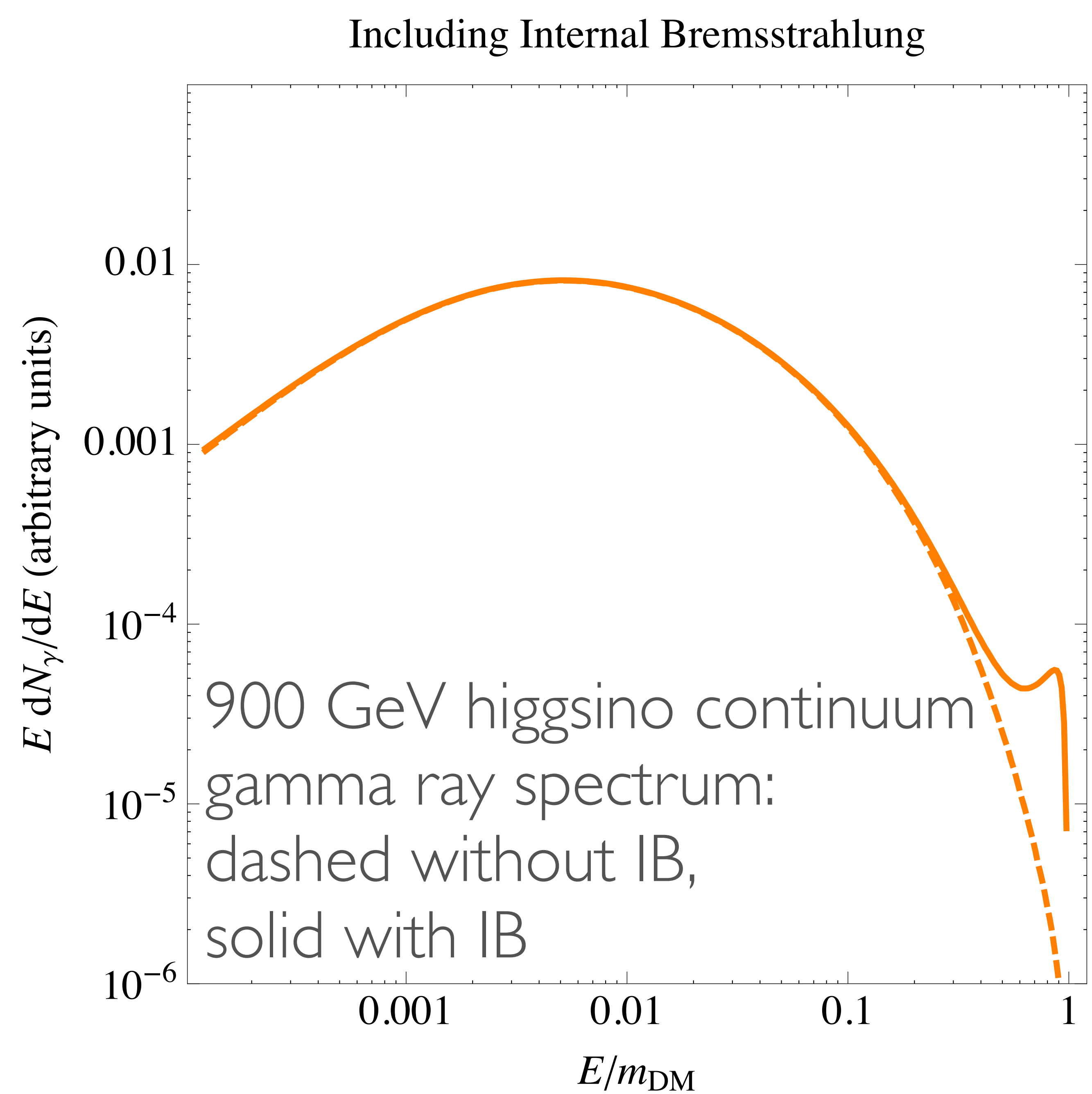
What astronomical observations would help us constrain this better?



INTERNAL BREM

Internal bremsstrahlung:

Alters shape of continuum photon spectrum; can look like enhanced line signal. Need to include in the fits: will get stronger bounds. (***Work in progress.***)



(see Bringmann, Bergstrom, Edsjo 0710.3169)

INTERPRETATION

Reheating just above BBN seems appealing in split SUSY: get a 125 GeV Higgs, possibly have an anthropic story, simple anomaly mediation works.

If that was the right story, we would have expected to see signals of wino annihilation. The bound on the reheating temperature is well above the BBN scale.

Disfavors the nonthermal scenario, ***unless* the winos decay**. Consider RPV + split? Or: preserve *R*-parity, but decay to hidden sector?

NONSTANDARD AXION COSMOLOGY

(e.g. Kawasaki, Moroi, Yanagida, hep-ph/9510461)

If wino DM decays through RPV, maybe *axions* are the DM.
Axions begin to oscillate **during moduli domination**.
Then moduli decay and produce entropy.

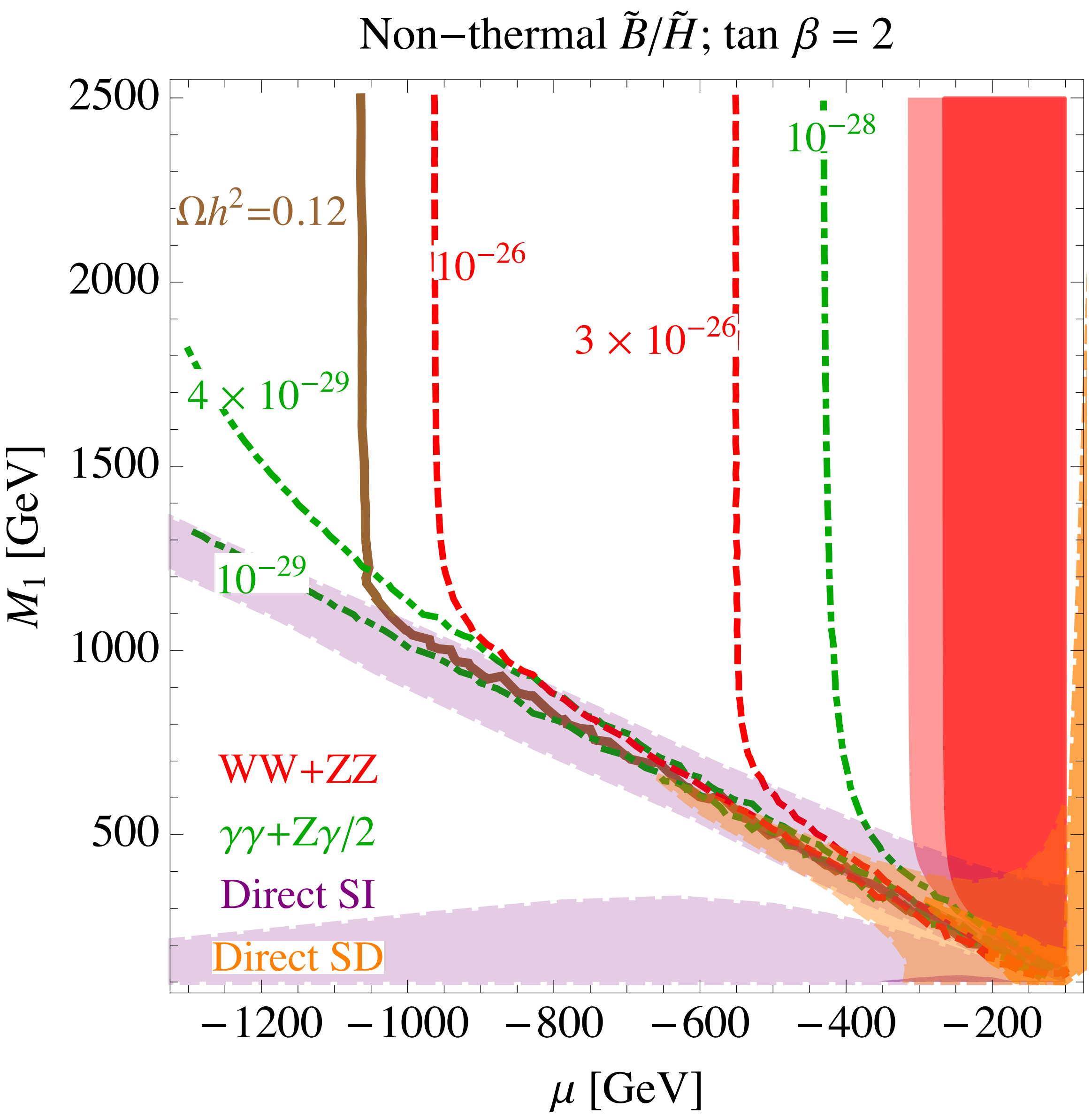
First, constant $\rho_a/\rho_{\rm modulus} \sim f_a^2\theta^2/M_{\rm Planck}^2$

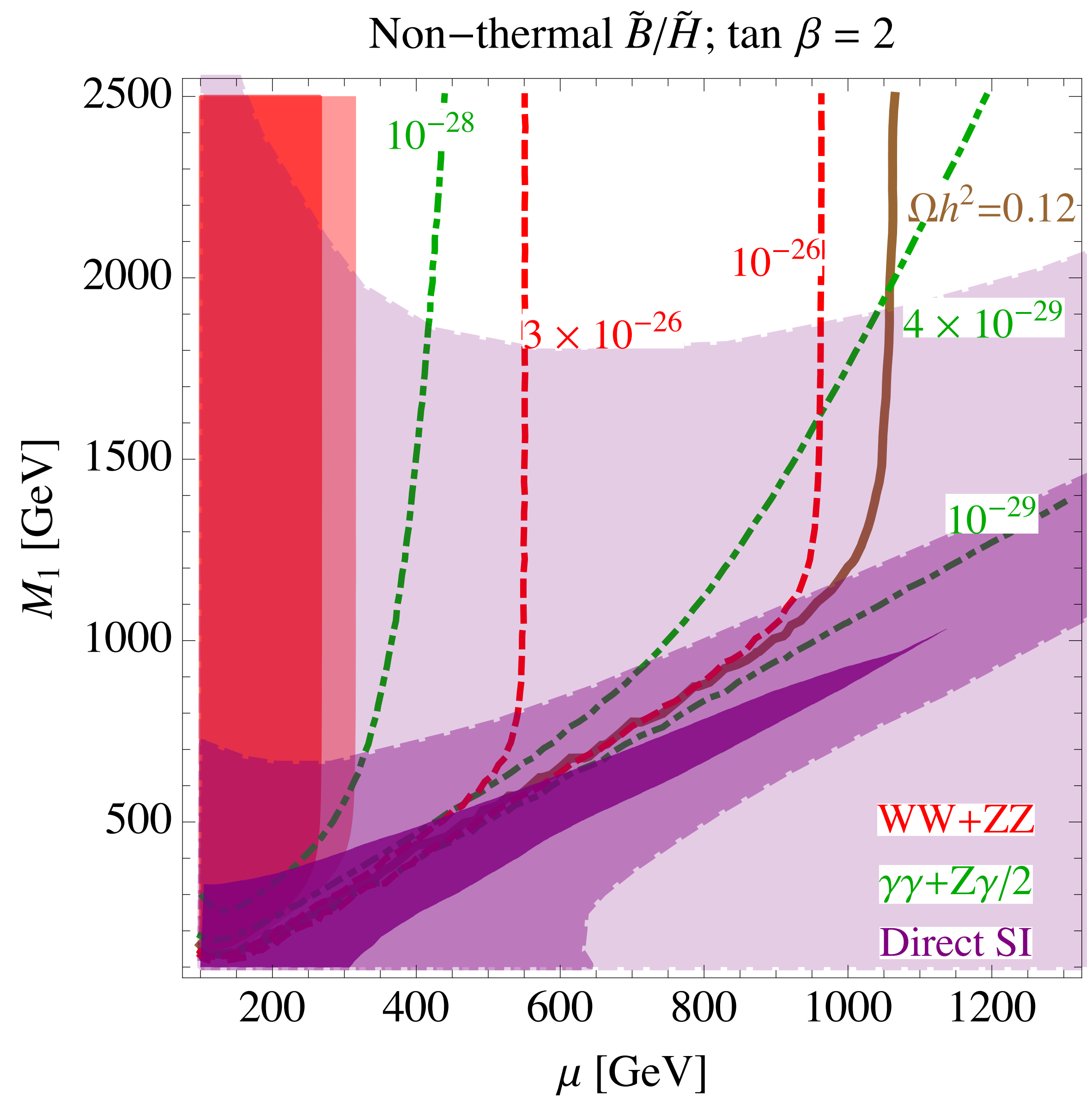
Modulus decay: $\rho_{\rm modulus} \sim g_* T_{\rm RH}^4$

Hence: $n_a/s \sim T_{\rm RH} f_a^2 \theta^2/M_{\rm Planck}^2$

$$\Omega_a \sim 5\theta^2 \left(\frac{T_{\rm RH}}{1~{\rm MeV}}\right)\left(\frac{f_a}{10^{16}~{\rm GeV}}\right)^2$$

BINO/HIGGSINO DM





CONCLUSIONS

Indirect detection is a very powerful complementary probe to direct detection.

A previously compelling scenario of nonthermal wino DM is ruled out, unless the reheating temperature is significantly higher. Moduli-induced gravitino problem remains.

Better: get rid of winos with RPV, but have axions with high-scale decay constant? Interesting "split-RPV" scenario to explore. Or: winos decay to hidden sector.